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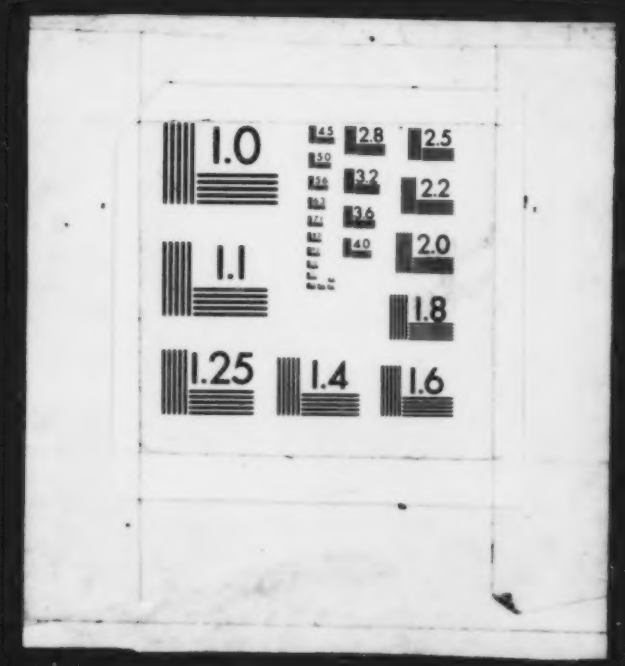

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Efficiency of Soil Core and Soil-Pore Water Sampling Systems

Texas Agricultural Experiment Station
College Station

Prepared for

Robert S. Kerr Environmental Research Lab.
Ada, OK

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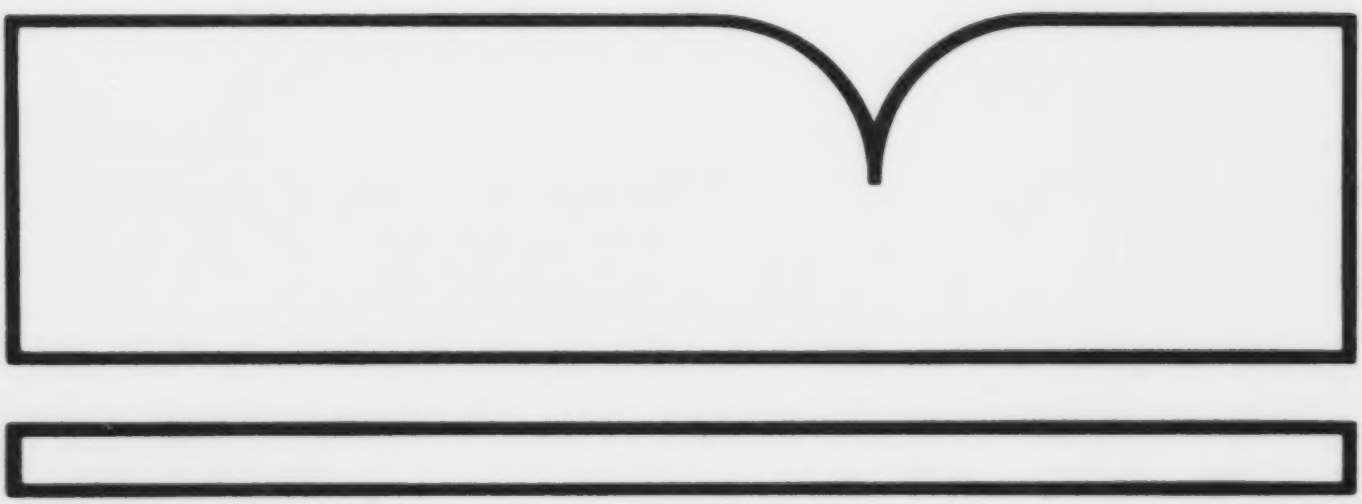

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Efficiency of Soil Core and Soil-Pore Water Sampling Systems

by

K. W. Brown
Texas Agricultural Experiment Station
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Cooperative Agreement CR-810945-01

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16. ABSTRACT

A laboratory column and field lysimeter study were conducted to evaluate the efficiency of soil core and soil-pore water samples to detect the migration of the organic components of land treated wastes through soil. In the laboratory, column leaching studies were performed by packing sieved soil into glass columns 35 cm x 4.6 I.D. A Bastrop clay, Norwood silt loam, or Padina loamy sand was amended with an API separator sludge (API), a solvent recovery sludge (SRS) or a wood preserving waste (WPW). A total of ten pore volumes of leachate were collected from the columns and analyzed for the bromide spike and selected organic chemicals.

The results from the laboratory column study were used to design the field lysimeter study. Large undisturbed monoliths of the Bastrop, Norwood, and Padina soils were collected and equipped with an underdrain system. Porous ceramic cups were installed at three depths in the monoliths. Soil core and soil-pore water samples collected periodically were monitored for eleven chemicals in the WPW amended soils, eight chemicals in the SRS amended soils, and nineteen chemicals in the API waste amended soils. The relative efficiencies of the two sampling methods were compared as a function of chemical structure and octanol-water partition coefficient.

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FOREWORD

EPA is charged by Congress to protect the Nation's land, air and water systems. Under a mandate of national environmental laws focused on air and water quality, solid waste management and the control of toxic substances, pesticides, noise and radiation, the Agency strives to formulate and implement actions which lead to a compatible balance between human activities and the ability of natural systems to support and nurture life.

The Robert S. Kerr Environmental Research Laboratory is the Agency's center of expertise for investigation of the soil and subsurface environment. Personnel at the Laboratory are responsible for management of research programs to: (a) determine the fate, transport and transformation rates of pollutants in the soil, the unsaturated and the saturated zones of the subsurface environment; (b) define the processes to be used in characterizing the soil and subsurface environment as a receptor of pollutants; (c) develop techniques for predicting the effect of pollutants on ground water, soil and indigenous organisms; and (d) define and demonstrate the applicability and limitations of using natural processes, indigenous to the soil and subsurface environment, for the protection of this resource.

Evaluation of the two methods proposed in EPA's regulations to measure pollutant transport in the treatment zone is required to perform a complete mass balance so that it is assured that the tenets of land treatment, i.e., degradation, transformation, and immobilization, are satisfied. This project was undertaken to evaluate both soil coring and pore water suction sampling as to their effectiveness in defining the vertical profile of fast moving organic chemicals in the unsaturated zone. The study was conducted in a limited number of soils and wastes using laboratory soil columns and 55-gallon barrel lysimeters. A comparison was made of the two methods as to efficiency in sampling specific organic compounds under simulated land treatment conditions.

Clinton W. Hall

Clinton W. Hall
Director
Robert S. Kerr Environmental
Research Laboratory

ABSTRACT

A laboratory column and field lysimeter study were conducted to evaluate the efficiency of soil core and soil-pore water samples to detect the migration of the organic components of land treated wastes through soil. In the laboratory, column leaching studies were performed by packing sieved soil into glass columns 35 cm x 4.6 I.D. A Bastrop clay, Norwood silt loam, or Padina loamy sand was amended with an API separator sludge (API), a solvent recovery sludge (SRS) or a wood preserving waste (WPW). A total of ten pore volumes of leachate were collected from the columns and analyzed for the bromide spike and selected organic chemicals. For both the Bastrop clay and Padina loamy sand amended with the API waste, breakthrough of hydrocarbons having 16 to 29 carbon atoms were found to occur in the leachate from the columns at 1 to 2 pore volumes. Breakthrough of isophorone from the loam and clay soils amended with the SRS waste occurred between 3 and 5 pore volumes, with a maximum concentration of 28 $\mu g\ L^{-1}$ detected in the leachate from the clay columns. Although there was no distinct breakthrough of isophorone in the sand, the maximum concentrations were detected in the 1 and 6 pore volume leachate samples.

Although eleven compounds were traced in the columns amended with the wood preserving waste (WPW), only two, pentachlorophenol and 2,4-dimethylphenol, were detected in high concentrations in the leachate. The concentration of pentachlorophenol in the leachate reached 9000 $\mu g\ L^{-1}$, 2500 $\mu g\ L^{-1}$ and 1600 $\mu g\ L^{-1}$ in the clay, sand, and loam soils, respectively, and reached peak concentration between 5 and 8 pore volumes. The 2,4-dimethylphenol reached a peak concentration between 2 and 3 pore volumes, and exhibited maximum concentrations of 4200 $\mu g\ L^{-1}$, 200 $\mu g\ L^{-1}$ and 6.5 $\mu g\ L^{-1}$ in the clay, sand, and loam soil, respectively. The results from the laboratory column study indicate that chemical structure and soil texture will have a major influence on the mobility of organic chemicals in soil. Long chain alkanes were leached rapidly through the soil but appeared in low concentrations, while pentachlorophenol leached more slowly but was detected in high concentrations. For the API and SRS wastes, breakthrough occurred at similar pore volumes for the sand, clay, and loam soils; however, for the WPW waste amended soil, breakthrough for the majority of chemicals occurred at smaller pore volumes in the clay followed by the loam and sand.

The results from the laboratory column study were used to design the field lysimeter study. Large undisturbed monoliths of the Bastrop, Norwood, and Padina soils were collected and equipped with an underdrain

system. Porous ceramic cups were installed at three depths in the monoliths. Soil core and soil-pore water samples collected periodically were monitored for eleven chemicals in the WPW amended soils, eight chemicals in the SRS amended soils, and nineteen chemicals in the API waste amended soils. Polynuclear aromatic hydrocarbons (PNA), as well as alkanes with greater than about 10 carbons and pentachlorophenol were preferentially adsorbed to the soil which made soil core samples most efficient for detecting these chemicals. Phenols, chlorinated and nitrogenated phenols, cresols, and aromatics were all weakly adsorbed by all three of the soils and thus were fairly randomly sampled by either the soil-pore water or soil core samples. However, for the aromatic constituents of the SRS waste, in general a higher percentage of samples had these constituents in the soil-pore water samples than in the soil core samples. Thus, for chemicals with octanol water partition coefficients (log K_{ow}) of 4 or larger soil-pore, water samples will be largely ineffective in detecting these chemicals. Chemicals having log K_{ow} values of 3 or less will generally be found in soil-pore water samples and transition chemicals (log K_{ow}'s between 3 and 4) have apparently an equal probability of being detected by soil core or soil-pore water sampling techniques.

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SECTION 1

INTRODUCTION

Unsaturated zone monitoring systems are required at hazardous waste land treatment facilities to determine if pollutants are moving beneath the treatment zone. Recent Federal legislation (Federal Register, 1985) now requires that soil-pore water samples and soil core samples be used to detect the presence of contaminants. Soil-pore water samples are intended to provide information on the movement of "fast moving" hazardous constituents and soil core samples are intended to provide information on "slower moving" constituents (Federal Register, 1982). Several in-depth reviews have discussed current soil-pore water and soil core sampling equipment and installation, operation, and sampling procedures (Wilson, 1980; Everett et al., 1982; USEPA, 1984). However, the question as to the efficiency of soil core and soil-pore water samplers in monitoring the movement of chemicals, particularly organic chemicals, in the unsaturated zone remains unresolved.

There are a variety of soil-pore water sampling devices but the porous ceramic cup has been the primary monitoring tool used. Porous ceramic cup samplers offer the advantages of ease of installation, ability to sample unsaturated soil, good performance under saturated conditions, and nondestructive continuous sampling at a point. Although porous ceramic cup samplers have been widely used, researchers have identified problems with their use. Barbee (1983), USEPA (1984), and Brown (1986) discuss the porous ceramic cup samplers limitations as reported in the literature.

Despite the large volume of data collected using porous ceramic cups, most of the information concerns inorganic constituents and very little information can be found concerning the interaction a porous ceramic cup has with organic chemicals. In a laboratory study using pesticides, Tsai et al. (1980) reported that ppDDD and ppDDT were completely attenuated and ppDDE was reduced 75 percent in concentration when passed through ceramic material via gravity flow. They speculated that the ppDDE was not retained by the cup to the extent of the ppDDD and ppDDT because of its smaller molecular size. In another laboratory study, Smith and Carsel (1986) indicated that the sorption of the pesticide aldicarb was insignificant when drawn through the porous ceramic cup. In contrast to ppDDE, ppDDD, and ppDDT which have low water solubility and a strong capacity to be adsorbed by the ceramic cup, aldicarb has a very high water solubility and therefore would tend to remain partitioned in the water and not be adsorbed by the ceramic

cup. Porous ceramic cups can be considered an extension of the soil, thus if chemicals are readily adsorbed by the soil they will very likely be adsorbed to some extent by the porous ceramic cup. Brown et al. (1985a) were able to use porous ceramic cups (50 kPa bubbling pressure) to monitor the movement of hazardous constituents in a complex wood preservative waste applied to soil. They found that anthracene, phenalene, tetrachlorophenol, pentachlorophenol, and several other compounds could pass through the ceramic material. However, it is not known if these or other compounds were partitioned out or adsorbed by the ceramic cup.

A potential problem encountered when using vacuum in porous ceramic cups to sample for organic chemicals is that volatile chemicals collected may be lost before the sample can be retrieved. Barbee and Brown (1986b) reported large losses of xylene from soil-pore water samples when vacuum was applied to porous ceramic cups for even as short a time as 15 minutes. It would be necessary to use an adsorbant trap to collect volatilized organic chemicals when using porous ceramic cup samplers (Wood et al., 1981).

Uncertainty remains as to whether the soil-pore water sample obtained by the porous ceramic cup is representative of the kind and amount of organic chemicals present in the soil solution. Many organic chemicals are not at all or only sparingly soluble in water and move in the unsaturated zone as a separate, immiscible phase, probably as thin films floating on the water. Such behavior, coupled with differences in density, viscosity, surface tension, volatility, soil water content, and soil pore size distribution, creates a very heterogeneous soil solution. When the porous ceramic cup extracts soil-pore water, it is very possible that one phase or the other may be preferentially sampled thus biasing the results. Barbee and Brown (1986b) found that xylene movement in natural field soils was very dependent upon the soil moisture content and structural characteristics. When the soil was near field capacity, the larger pores were filled with water and the xylene could not move through the soil. However, when the soils were at moisture contents less than field capacity, large quantities of xylene moved quite rapidly to at least 61 cm depth. When soil-pore water samples were taken, this non-uniform flow of xylene and water caused the xylene to be missed by the porous ceramic cup samplers. Likewise, Barbee and Brown (1986b) observed that in soils with strong structural development, xylene moved almost exclusively through macropores between the three dimensional structural units (peds) and completely circumvented the porous ceramic cup samplers so that only trace quantities of xylene were collected by the porous ceramic cups while pure xylene was being collected by free drainage pan samplers at the same depth. They postulated that because xylene is hydrophobic it tended to remain concentrated in the macropores and could not easily diffuse through water films into the soil matrix. The pan samplers, having a large surface area, intercepted some of the macropores and were able to obtain a fairly accurate sample. Schwille (1984) conducted

laboratory experiments using glass plates to simulate fissured media and applied various organic chemicals which he infiltrated through the media. He also found that organic chemicals are rapidly percolated through the unsaturated zone via macropores. Both Shaffer et al. (1979) and Barbee and Brown (1986a) using inorganic tracers found that porous ceramic cups were inadequate for monitoring the movement of water and chemicals in the unsaturated zone of strongly structured soils.

Soil samples are best suited for determining the presence of contaminants that migrate slowly as a front through soil profiles. There is increasing evidence that in most structured soils, mobile constituents do not move in well defined fronts. Barbee and Brown (1986b) reported that spilled xylene moved in a front only in very sandy soils; however, in the more structured clay loam and clay soils, migration occurred in the cracks and channels. Dye studies (Anderson and Bouma, 1977 and Brown et al., 1983b) have been used to present visual evidence for this pattern of movement through structured subsoil. Land treatment facilities are typically not placed on deep sandy soils because of the increased risk of contaminant migration. Thus, most of the soils at the bottom of the treatment zone where samplers would be installed would be expected to exhibit structural characteristics. Migrating chemicals are expected to be found only in or immediately adjacent to the cracks or large pores in these soils. Therefore, if a soil sample is taken from the center of a ped, the presence of a contaminant may be entirely missed. However, if a sampler intercepts a conducting channel, the presence of the contaminant should be evident in an analysis but will likely exceed the average concentration of the contaminant at that depth. Therefore, for soil samples to provide adequate data on the presence of mobile constituents, either replicate samples must be taken, which could be composited, or single samples large enough to include a representative crossection of the structural units are needed. Even this procedure may not be entirely satisfactory, since it is possible that if contaminants occur in low concentrations, they will be further diluted by the soil inside the peds and result in concentrations below the detection limits. An additional difficulty is the scant information available in the literature on the size of sample required to be representative. Bouma and Dekker (1978) investigated the frequency of the spacing of cracks in the soil and reported that conductive channels occurred in a clay soil in a rather regular pattern at a spacing which averaged 62.5 cm^2. This large spacing suggests that samples much larger than those normally taken would be required.

In addition to the problems of collecting a representative sample on a scale of the peds, i.e., on a microscale, the additional problem exists of collecting representative samples of the different units of soil that may occur within a given facility. A detailed soil survey should assist with decisions as to where and how many samples may be needed. Even then, however, unmapped heterogeneities may result in a broad range of soil characteristics, i.e., the hydraulic conductivity (Nielsen et al., 1973). Such heterogeneities in soil properties

will impact the number per unit area of both soil core and soil-pore water samples needed to characterize the flow of leachate and possible contaminants toward the groundwater.

Two additional considerations are the need to take precautions against possible cross contamination between soil samples taken from different layers and the need to refill the sampling holes to prevent short circuiting of runoff or leachate following sampling. Cross contamination is a particularly troublesome problem when the surface horizon is highly contaminated with waste and is of a loose and friable nature. To prevent this soil from falling down the sampling hole and contaminating lower samples, it is often desirable to remove the contaminated soil from some distance around the sampling hole and surround the sampling hole with a pipe or container that is open on both ends.

Care must be taken to repack sampling holes with clean fill. It may be desirable to use bentonite to fill bore holes. The different color and texture of bentonite should also serve to label the soil and minimize the possibility of a later sample being taken in the same location.

Several field studies have been conducted to investigate the efficiency of soil-pore water and soil core samples in monitoring the unsaturated zone below land treated petroleum refining and wood preservative wastes. The first study (Law Engineering, 1982) was carried out at three petroleum refinery waste land treatment facilities located in west Texas, Louisiana, and Ohio. The conclusions they drew from the literature review and field evaluation were summarized as follows:

> There are a number of inherent limitations to the use of porous ceramic cups. They can extract soil-pore water only from moist soil in which the water is held at less than about 80 kPa tension. The volume of soil from which the porous ceramic cup extracts water is unknown and varies with water content of the soil. Thus, the porous ceramic cup's ability to collect a soil-pore water sample of sufficient volume decreases with decreasing soil water content and as soil texture becomes finer. When the soil is too dry for successful porous ceramic cup soil-pore water sample collection, there is little soil water movement, and consequently, little or no waste constituent migration. In the field evaluation, a sample was collected only 17 and 23 percent of the time at the west Texas and Louisiana sites, and of the samples collected, none were sufficient to meet the 155 ml volume required for constituent analysis. At the Ohio site, 78% of the sampling attempts yielded a sample, yet only 70% of those samples

collected during the wettest soil condition had the required 155 ml volume. Because of the limited samples and sample volume, statistical analysis of the data were restricted. Soil core extracts included the pore water held at all tensions, not just that sampled by the porous ceramic cup, plus some of the less tightly adsorbed constituents, thus there were no instances when analyzed constituents were found by one monitoring method and not by the other. Comparison of concentrations from soil core and soil-pore water samples revealed that immobile constituent concentrations were greater in the soil core and mobile constituent concentrations were greater in the porous ceramic cup soil-pore water samples. There was no difference between concentrations in samples collected by ceramic cups with different pore sizes.

Therefore, Law Engineering (1982) concluded that porous ceramic cup soil-pore water samples are not suitable for mass balance determinations nor do they provide a reliable means of monitoring the unsaturated zone of a refinery land treatment facility.

Law Engineering data underscore some of the common problems encountered when porous ceramic cup samplers are used to take in situ soil-pore water samples. Brown (1986) however, found that porous ceramic cups have provided adequate samples in medium and coarse textured soils for several years, provided the soils were not calcareous. In calcareous soils, the periodic flushing of the cups with a dilute HCl solution was necessary. Law Engineering also required 155 mL of sample for both organic and inorganic constituent analysis. However, a much smaller sample volume may be adequate for analysis if a procedure similar to that developed by Giam et al. (1980) is used for organic chemical analysis.

In the second study, a wood preservative waste was land treated on a silt loam soil contained in barrel sized lysimeters (Brown et al., 1985a). Leachate from the bottom of each lysimeter was collected through 3 porous ceramic cups and compared to soil cores taken from the center of each lysimeter at depths of 0 to 15 cm, 15 to 45 cm, and 45 to 90 cm. The results from this study are summarized as follows:

A considerably greater number of different chemicals were found in the soil core samples than from the soil-pore water samples. Saturated alkanes, branched alkanes, alkanols, and polynuclear aromatic hydrocarbons were identified in soil core samples, while compounds such as tetra- and pentachlorophenol, phenalene, and anthracene were identified in the soil-pore water samples. Phenalene and tetrachlorophenol were not detected in the soil core samples at any depth.

Brown et al. (1985a) concluded that both soil core and soil-pore water samples are necessary to provide an accurate evaluation of

the potential for hazardous waste constituents to migrate below the zone of incorporation at a land treatment facility. However, because the porous ceramic cup samplers did not obtain a sample of the pore water moving through the soil profile but merely collected that leachate which reached the bottom of the barrel lysimeter, it is still necessary to determine the efficiency of soil-pore water and soil core samplers in sampling and detecting organic chemicals that are migrating beneath the zone of waste incorporation at a land treatment facility.

SECTION 2

CONCLUSIONS

1. Laboratory soil columns (packed, saturated, nonsterilized) have some predictive value for estimating the rate at which chemicals of diverse properties move through soils. However, in natural field soils factors such as structural development, unsaturated flow or variable physical properties may greatly increase or decrease the rate at which chemicals move.

2. Laboratory soil column data for the sand and clay soils showed that peak concentrations of the alkanes occurred after 2 pore volumes of leachate passed through the soil. It was estimated that only 0.02% of the total amount of alkanes applied to the sand soil were leached through the column after 10 pore volumes of flow.

3. Laboratory soil column data indicated that isophorone, the major SRS waste constituent, reached peak concentrations at about 2 pore volumes in the sand soil and at about 4 pore volumes in the loam and clay soils.

4. In the laboratory columns, pentachlorophenol began appearing in the leachate after about 3.5 pore volumes passed through all three soils, but only in the loam soil did it show a definite peak which occurred at about 6.5 pore volumes. In the sand and clay soils, pentachlorophenol appeared to continually increase in concentration even after 10 pore volumes of leachate had been passed through the columns. For 2,4 dimethylphenol, peak concentration in the leachate occurred at about 3 pore volumes for all three soils.

5. In the laboratory columns, PNA compounds began appearing in the leachate at about 3 pore volumes.

6. Soil-pore water sampling would be preferable to monitor the movement of alkanes having 10 or fewer carbons, while soil core samples would be best for monitoring alkanes with greater than 10 carbons.

7. Except for phenanthrene, PNA compounds occurred almost exclusively in soil core samples. Because of their tendency to be preferentially adsorbed by soil, soil core samples are more efficient than soil-pore water samples for sampling PNA compounds.

8. Phenol, chlorinated and nitrogenated phenols, and cresols were weakly adsorbed by the soils and thus were fairly randomly sampled by both soil core and soil-pore water techniques. Pentachlorophenol, due to its higher octanol water partition coefficient (5.01), was more strongly adsorbed to the soils and thus was best sampled by the soil core technique.

9. Constituents of the SRS waste (aromatics) were weakly adsorbed by the soils and were fairly randomly sampled by both soil core and soil-pore water techniques. In general, a higher percentage of samples containing measurable quantities of constituents occurred in the soil-pore water samples. Of the three wastes studied, the SRS had by far the greatest percentage of samples which contained a given waste constituent in both the soil core and soil-pore water samples.

10. A statistical analysis of the concentrations of the waste constituents in a soil sample versus the concentrations found in the corresponding soil-pore water sample indicated there was considerable variability between the samples. Thus, because of this variability, even when a chemical was preferentially partitioned into either the soil-pore water or onto the soil, the concentrations did not differ significantly at $p = 0.05$.

11. Soil-pore water samples were obtainable more often from the sand soil than from the finer textured silt loam and clay soils.

12. Chemicals having high K_{ow} values (10^4 and larger) were adsorbed by the soil and thus soil-pore water samples were ineffective in detecting their presence. However, occasionally chemicals having K_{ow} values greater than 10^4 moved to significant depths (61 cm) despite their preferential adsorption by the soil. Chemicals having low K_{ow} values (less than 10^3) were weakly bound to the soil and were generally found in the soil-pore water samples. Transition chemicals, those with K_{ow} values between 10^3 to 10^4 have an equal probability of being detected by soil core or soil-pore water sampling techniques.

SECTION 3

RECOMMENDATIONS

The partitioning characteristics of the waste constituents should be utilized to select between soil-pore water and soil core sampling techniques. Soil-pore water samples should be collected for chemicals with octanol water partition coefficients of 10^3 or less, while soil core samples should be collected when sampling for chemicals with octanol water partition coefficients greater than 10^4. Transition chemicals with octanol water partition coefficients between 10^3 to 10^4 appear to be randomly sampled by either technique. Most land treatable hazardous wastes contain a complex mixture of constituents with a broad range of octanol water partition coefficients. Thus, it is recommended that both soil samples and soil-pore water samples be taken when monitoring the treatment zone of a land treatment facility.

Due to considerable spatial variability encountered in the unsaturated zone of soils, particularly in strongly structured soils, chemical and water movement do not take place as a uniform front. This, coupled with the diverse properties of the waste constituents and their interaction with soils, may result in a nonhomogeneous soil solution. Thus, further work should be directed toward developing improved methods or techniques to collect samples that integrate over larger areas and time spans and thus provide samples which are more representative of the soil solution composition and which more accurately estimate the flux of contaminants moving toward the groundwater.

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SECTION 4

MATERIALS AND METHODS

EXPERIMENTAL DESIGN

A two-phased program, consisting of laboratory soil columns and field barrel lysimeters containing undisturbed soil monoliths, was designed to determine the efficiency of porous ceramic cup samplers and soil core samples to detect the migration of organic chemicals through soil.

A preliminary laboratory soil column study was done in duplicate using three soils and three wastes. The soil columns were not sterilized and were maintained at saturation. The primary objective of this phase was to determine the rate of waste constituent movement as a function of pore volumes of water leached through the soil column. This data provided the means for designing the sampling schedule for the field barrel lysimeters.

Once the relationship between chemical breakthrough and the pore volume of leached liquid was determined, a field study was conducted using undisturbed soil monoliths contained in barrel sized lysimeters. Thirty-six barrel lysimeters were constructed, 12 each from profiles of the three soils used in the laboratory soil column study. The three wastes used in the laboratory study were applied to the barrels so that three barrels of each soil received one waste, with the remaining three barrels of each soil serving as controls. Soil-pore water and soil core samples were taken on a time schedule according to the number of pore volumes of leachate that had been collected from the bottom of the barrels. Thus, the soils could be sampled at the optimum time to catch the peak concentration of chemicals at a particular depth. Likewise, the laboratory and field data could be directly compared through the number of pore volumes of leachate collected.

Soils

The same three soils were used for both the laboratory soil columns and field barrel lysimeters (Table 1). They were selected to provide a range in physical and chemical properties and included a Bastrop clay (Udic Paleustalfs), Norwood silt loam (Typic Udifluvents), and Padina loamy sand (Grossarenic Paleustalfs). In the laboratory column study, only the surface soil of each soil type was used.

TABLE 1. CHARACTERISTICS OF UNDISTURBED SOILS

Soil Series	USDA Texture	CEC meq/100g	Carbon %	pH	Bulk Density g/cm^3
Bastrop	Clay	27.4	1.0	6.9	1.49
Norwood	Silt Loam	19.6	1.4	7.7	1.44
Padina	Loamy Sand	4.3	0.4	6.5	1.38

Wastes

Three listed hazardous wastes were selected based upon the criteria of finding at least twenty organic chemicals of diverse properties i.e., polarity, water solubility, functional groups, etc., that were commonly found in wastes that are land treated or are frequently released into the soil environment. The selected wastes included an API separator sludge (API) from the petroleum refining industry, a solvent recovery sludge (SRS) produced from reclaiming nonhalogenated solvent-containing wastes, and a chlorinated wood preserving waste (WPW) from a pine wood treatment plant. Initial identification of the major chemical constituents in each waste was done using a Hewlett-Packard Model 5970 Mass Spectrometer (MS)* interfaced with a Model 5880 Gas Chromatograph (GC). The major constituents in each waste are summarized in Table 2. A complete quantitative analysis of the wastes was unsuccessful due to the complexity of the wastes; therefore, the total solvent extractable organics was determined. The extractable organics were 5, 13, and 34% (wet weight basis) for the API, SRS, and WPW wastes, respectively. It was decided to spike naphthalene, xylene, toluene, and ethylbenzene into the SRS waste to raise their concentrations to detectable levels should they move through the soils. This was done by thoroughly mixing a liter of HPLC grade solvent of each chemical into a 55 gal drum of the sludge, and allowing it to equilibrate for two weeks before use.

Laboratory Columns

Column leaching studies were performed by packing nonsterilized sieved soil into 35 cm x 4.6 cm ID glass columns plugged with solvent washed glass wool (Figure 1). Twenty-eight cm of soil were added by layers, tamped, and scarified in order to achieve a consistent bulk density approaching common field values. Five percent (by weight) of the dry soil was removed from the top of each column, wetted with distilled

*Mention of brand names do not constitute an endorsement.

TABLE 2. THE MAJOR CHEMICAL CONSTITUENTS OF THE WASTES USED IN THE LABORATORY AND FIELD STUDIES

Waste	Base/Neutral	Acid
API	Alkanes (C10 - C30)*	
	Polynuclear Aromatic Hydrocarbons (PNA's)**	Dimethylphenol
	Acenaphthene	Dinitro-o-cresol
	Acenaphthylene	Dinitrophenol
	Anthracene	
	Chrysene	
	Fluoranthene	
	Fluorene	
	Naphthalene	
	Phenanthrene	
	Pyrene	
SRS	Acetophenone*	Ethylbenzene
	2-Butoxyethanol	
	Ethylbenzene	
	Isophorone†	
	2-phenyl-2-propanol	
	1,2,4-Trimethylbenzene	
	Toluene	
	Xylenes	
	PNA's ††	
	Acenaphthylene	Acenaphthylene
	Fluoranthene	Fluoranthene
	Fluorene	Fluorene
	Naphthalene	Phenanthrene
	Phenanthrene	Pyrene
	Pyrene	
WPW	PNA's	
	Acenaphthene	Dibenzofuran*
	Anthracene	2,4-Dimethylphenol
	Fluoranthene	2,4-Dinitro-o-cresol
	Fluorene	4,6-Dinitro-o-cresol
	Methylnaphthalene	2,4-Dinitrophenol
	Phenanthrene	4-Nitrophenol
	Pyrene	p-chloro-m-cresol
		Pentachlorophenol
		2,4,6-Trichlorophenol

* Fraction selected for tracking.
** Tracked in the field barrel lysimeters only.
† Only chemical tracked in the laboratory columns.
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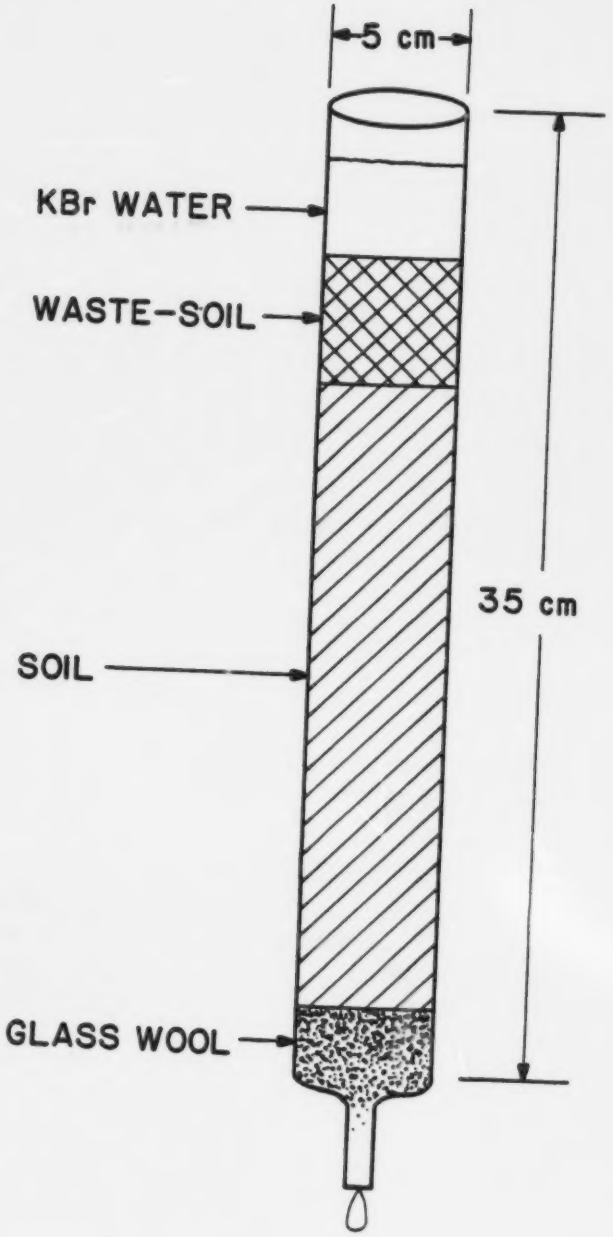

Figure 1. Laboratory soil column used to conduct leaching studies.

water to saturation, and mixed with waste at a rate of 5% (w/w) of the entire soil column. Before the soil-waste mixture was put back on top of the column soil, the column soil was saturated with distilled water. Immediately after the soil-waste mixture was applied, a one liter volumetric flask containing 150 mg L^{-1} bromide in solution was inverted over the column and held at a level that maintained a 3 cm head of liquid on the soil surface. The bromide, being practically nonadsorbed by the soils, provided a reference to compare with the breakthrough of the organic chemicals. The soils were leached with ten pore volumes of water. For the first pore volume of leachate, the liquid was fractionated into one-tenth pore volume samples. From 2 to 10 pore volumes, samples were taken in two-tenth pore volume increments. Samples were frozen immediately after being collected until analysis for bromide and the organic chemicals were completed. Table 3 lists the laboratory soil column parameters.

Leachate Chemical Analysis

Organics--

Due to the small sample volumes collected from the laboratory columns, the procedure developed by Giam *et al.* (1980) was used for organics extraction. The procedure calls for fractionating a 10 mL sample into base/neutral, and acid fractions and then extracting the fractions with petroleum ether. The extraction procedure for leachate samples is as follows:

1. Pipet 10 mL of sample into a 4 dram (16 mL) vial with teflon-lined cap.

2. Add sufficient quantity (∿ 4 drops) of 6N NaOH to raise sample to pH >12.

3. Extract with 1 mL petroleum ether for 1 minute. (Use methanol dropwise to disperse emulsion, if needed).

4. Remove petroleum ether layer with Pasteur pipet and place into a 1/2 dram (2 mL) vial with a teflon-lined cap and label base-neutral fraction.

5. Remove the sample from the 4 dram vial with a Pasteur pipet and place into another clean 4 dram vial. Do not carry over any residual petroleum ether from the base-neutral fraction.

6. Add sufficient amount (∿ 6 to 8 drops) of 6N HCl to lower sample to pH <2.

7. Extract with 1 mL petroleum ether for 1 minute.

TABLE 3. LABORATORY COLUMN PARAMETERS*

Waste	Soil	Dry Weight (g)	Bulk Density (g cm^{-3})	Porosity (%)	Pore Vol. (cm^3)	Waste Added (g)
API	Sand	690	1.50	43.5	200.82	34.5
API	Loam	638	1.38	46.9	216.40	31.9
API	Clay	672	1.43	42.8	200.86	33.6
SRS	Sand	706	1.50	43.2	202.98	35.3
SRS	Loam	628	1.36	47.7	219.94	31.4
SRS	Clay	677	1.43	42.8	202.64	33.8
WPW	Sand	733	1.56	41.3	194.80	36.6
WPW	Loam	651	1.38	46.8	220.00	32.6
WPW	Clay	709	1.45	42.1	194.59	35.4

* Bulk density, porosity, and pore volume values calculated from dry soil weight and bulk soil volume.

8. Remove petroleum ether layer with Pasteur pipet and place into a 1/2 dram vial with a teflon-lined cap and label acid fraction.

For all wastes, the alkanes, aromatics and PNA's were partitioned into the base/neutral fraction. The cresols and phenols from the WPW were partitioned into the acid fraction. After extraction, the samples were evaporated with a slow stream of purified N_2 to approximately 50 µL volume.

Initial identification of the organic chemicals in the samples was done on a Hewlett-Packard Model 5970 Mass Spectrometer (MS) interfaced with a Model 5880 Gas Ghromatograph (GC). The GC/MS was tuned using the chemical PFTBA and then normalized to DFTPP by the system computer. The analytical materials and conditions which were used for the analyses are given in Table 4. Once the chemicals of interest were positively identified on the GC/MS, the samples were quantified using a Tracor Model 560 Gas Chromatograph (GC).

For the acid fraction (phenols, cresols), 1-fluoronaphthalene and anthracene-D_{10} were used as internal standards, and for the base/neutral fractions (PNA's, alkanes, aromatics), a combination of 1-fluoronaphthalene, o-fluorophenol, 2,2'difluorobiphenyl, or benzo(a)anthracene-D_{12}, were coinjected as internal standards. Guidelines for selection and use of internal standards were obtained from Sauter et al. (1981).

Because of the sensitivity of the GC to organic contaminants, all glassware used in this study were first cleaned with "micro" soap (International Products, Inc.), rinsed with distilled water, solvent washed in acetone, rinsed with distilled water and put in a 450°F oven overnight. Glassware repeatedly being used, i.e., boiling flasks and Soxhlets, were soaked in a No-chromix (Godax Lab. Inc., N.Y.) H_2SO_4 acid bath for a minimum of two hours before washing. The soil moisture cans used for storing the soil core samples were washed in the same way as the glassware prior to use. Teflon lined caps were used in all sample and standard vials.

Bromide--

The laboratory soil column eluate was analyzed for bromide concentration using an Orion Model 901 Microprocessor Ionanalyzer coupled with an Orion Specific Ion Electrode (Bromide-Model #94-35A) and a Fisher Calomel Reference Electrode (Model #13-639-63). A sodium nitrate ionic strength adjuster was added to each sample to help increase the sensitivity of the bromide electrode.

Bromide concentrations were plotted versus pore volumes of leachate to visually determine the breakthrough curve for a nonadsorbed chemical.

TABLE 4. GC/MS AND GC OPERATING PARAMETERS

Parameter	GC/MS	GC	
Column	Fused silica 25 m x 0.2 mm ID 5% phenylmethyl silicone 0.33 µm film thickness (Hewlett Packard)	Fused silica 30 m x 0.53 mm ID (megabore) 100% methyl polysiloxane 1.5 µm film thickness (DB-1, J&W Sci., Inc.).	
Carrier Gas	Helium, 1 cc/min	Helium, 13.2 cc/min	
Injector	Splitless mode	Direct flash	
Injector Temp.	260°C	225°C	
Detector	Mass selective	FID	
Detector Temp.	280°C	300°C	
	Oven Temperature		
	(All chemicals)	(PNA's/Alkanes)	(Phenols/Aromatics)
Initial	4 min @ 50°C	2 min @ 50°C	2 min @ 50°C
Ramp	8°C/min	8°C/min	8°C/min
Final	13.5 min @ 270°C	4 min @ 275°C	1 min @ 225°C

Field Barrel Lysimeters

The technique used by Brown et al. (1985b) was followed for collecting barrel sized undisturbed soil monoliths (Figure 2). Briefly, the procedure involves gradually pushing a straight walled cylindrical casing (57 cm ID and 85 cm tall), which was mounted inside a steel support frame, down over a monolith of undisturbed soil by exerting vertical pressure with a backhoe bucket on a steel plate set on top of the frame. When the casing was filled to within 15 cm of the top, a 51 cm diameter plywood disc was put on the soil surface and two steel bars were put through four holes drilled in the top of the casing. Additional pressure was applied to the frame until the plywood came into firm contact with the steel bars. The monolith was then tipped slightly to break it loose from the underlying soil, lifted, and rotated to expose the bottom. The excess soil was trimmed to allow the installation of a lid (lysimeter bottom). Holes were carved out to allow three suction cups (Coors Type 7001 P-6-C) to be installed in the bottom of each monolith. The excavated soil was then refilled around the suction cups. A 2 cm vertical hole was drilled to the soil surface from the bottom of

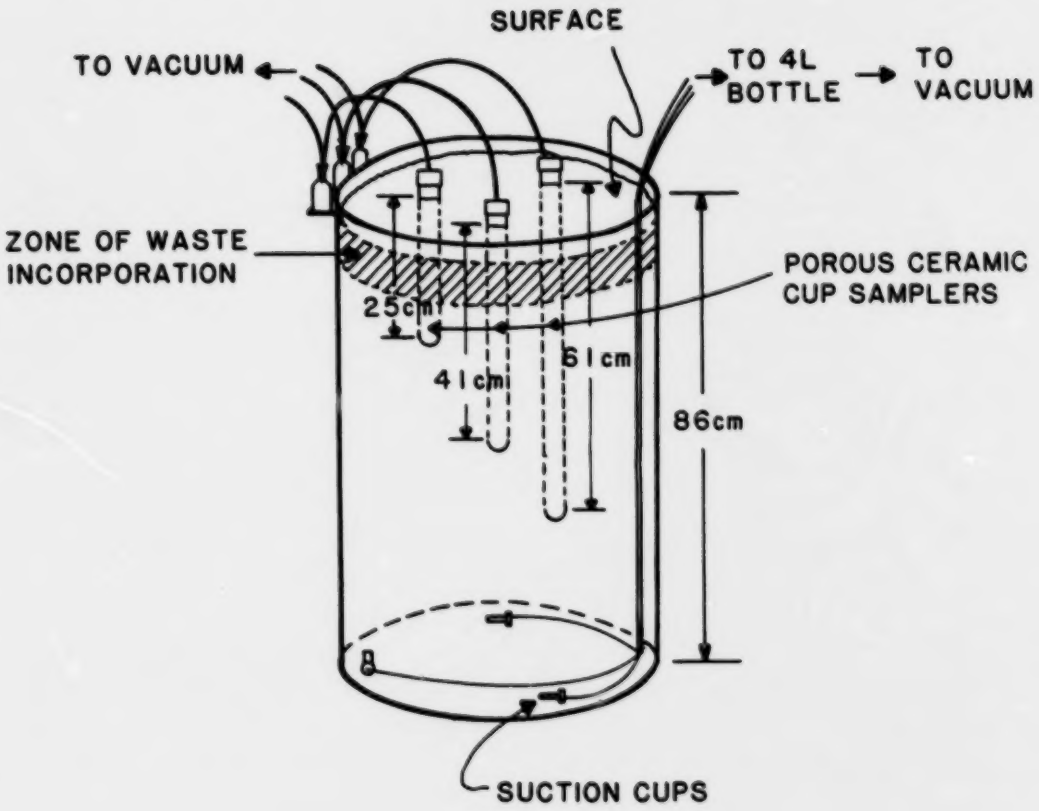

Figure 2. Undisturbed soil monolith contained in a barrel lysimeter equipped with the porous ceramic cup soil-pore water samplers.

the monolith, and a piece of 1.3 cm ID PVC pipe was inserted. Nylon tubes which were connected to the the suction cups were passed through the 1.3 cm PVC pipe to the soil surface and connected by means of a plexiglass manifold to a 4 L bottle. After installation of the suction cups, the casing rim was cleaned, a bead of silicone adhesive was placed on the rolled edge of the casing, and a sponge rubber gasket and lid were installed. A lever lock type clamp was used to attach the lid. The monoliths were then turned upright and transported to the experimental site.

To minimize the possibility of sidewall flow, a barrier was installed around the inside edge of each monolith. To accomplish this, a 15 cm depth of soil was removed from a barrel and stored in clean 5 gal buckets. The inside casing wall was washed with water and air dried. A 5 cm wide strip of duct tape was taped to the wall of the casing so that 3 cm of it bent out to overlap the soil. A second strip of duct tape was used to secure the first to the casing wall. Then, 5 cm of soil was replaced into the barrel on top of the duct tape and lightly packed, leaving the remaining 10 cm of soil to be mixed with the waste. The barrels were tested for breakthrough by observing the flow of a 200 mg L^{-1} bromide solution through them. The details of this procedure can be found in the paper by Brown et al. (1985b). Some of the barrels initially exhibited breakthrough of the bromide solution, due possibly to a slight dessication of the soils prior to water application. However, after wetting they did not exhibit preferential bromide movement. The barrels were also tested for their bulk flow rate before waste application and separated into groups of three having similar flow rates (Table 5). Such general groupings helped minimize the affects caused by differences in flow rates and dispersion on chemical mobility within a certain waste or soil treatment.

Soil-Pore Water Sampler (Porous Ceramic Cups)

The soil-pore water samplers used in this research were made from 6.2 cm long by 4.8 cm dia. porous ceramic cups with a 2 bar bubbling pressure (Soil Moisture Equipment Corp., Part No. 653X1-B2M2). This cup size was preferred over smaller porous ceramic cup sizes since it may be less affected by cup intake rate differences, provide a larger sample volume for analysis, and have lower failure rates (Silkworth and Grigal, 1981). Each sampler was made by cutting an appropriate length of 3.8 cm dia. ID schedule 40 PVC pipe and beveling the inside edge of one end to approximately a 45^{o} angle to ensure a snug fit with the neck of the porous ceramic cup. An inert epoxy (Armstrong A34) was used to glue the cup to the PVC pipe. Nylon tubing, 0.46 cm dia. OD, was passed through a 0.46 cm hole in a 3.8 cm dia. PVC endcap and glued inside and out with epoxy so that when the endcap was glued into the end of the sampler tube the nylon tubing would contact the inside tip of the porous ceramic cup. The nylon tube was cut at an angle to ensure that liquid could enter it even after being pressed against the porous ceramic cup. The PVC endcap was glued in place using primer and PVC cement. After the porous ceramic

TABLE 5. AVERAGE BARREL LYSIMETER BULK WATER FLOW RATES ($L\ DAY^{-1}$) BEFORE WASTE APPLICATION

Treatment	Soil		
	Bastrop Clay	Norwood Silt Loam	Padina Loamy Sand
	$L\ Day^{-1}$		
Controls	0.29*	0.64	0.59
API	0.12	0.94	0.51
SRS	0.14	0.82	0.84
WPW	0.18	0.74	0.81

* Average of three barrels.

cup samplers were assembled, they were submerged in water and subjected to a positive pressure. Any cup assemblies that had excessive bubbling were re-epoxied. After testing, the porous ceramic cups were rinsed in 0.1 N HCl and then distilled water.

Porous Ceramic Cup Sampler Installation--

The porous ceramic cup samplers were installed just after the duct tape barrier was installed. A 4.4 cm dia. auger was used to bore three vertical holes in a triangular configuration with 20 cm between them (Figure 2). The holes were excavated to depths of 28 cm, 44 cm, and 64 cm (from the original soil surface) so that the middle of the porous ceramic cups would be 25 cm, 41 cm, and 61 cm deep, respectively. A slurry of the removed soil and distilled water was made, and approximately 100 mL of the slurry was poured into each hole. The porous ceramic cup sampler was then inserted into the slurry and twisted slightly to remove any air pockets and provide a good contact with the undisturbed soil. Once in place, another 100 mL of slurry was poured into the hole. Thereafter, air dried, finely sieved soil was poured down around the sampler tube and packed with a long thin spatula. Once the space around the sampler tube had been completely backfilled, a 10.5 cm dia. disc of 4 mil polyethylene plastic was cut and slid down over the sampler tube. This polyethylene disc was then firmly secured to the sampler tube with duct tape to form a 2 cm wide water tight collar. This collar prevented the preferential movement of water and chemicals down the sides of the sampler tube and thus maintained the integrity of sample quality. There was no indication, i.e., contamination peak on the chromatographs, that the soil-pore water samples were contaminated from either the duct tape or polyethylene plastic. Once the sampler

collars and duct tape barrier were in place, 5 cm of soil was replaced in the barrels and tamped lightly. The remaining 10 cm of stored soil was mixed with the waste.

Soil-Pore Water Sampling Procedure--

To obtain a soil-pore water sample, each porous ceramic cup sampler was attached to a 60 mL capacity bottle that was plugged into a PVC vacuum line (Figure 2). A continuous 55.4 kPa (0.554 bar) vacuum was drawn on the samplers for 20 min. If the volume of the soil-pore water sample exceeded the capacity of the 60 mL sample bottle, part of the sample was discarded and the sample bottle was again connected to the sampler. This process continued until no more soil solution could be readily extracted. This procedure helped to minimize the amount of sample that remained in the porous ceramic cup to dilute or contaminate the next sample and also gave a composite sample of the total volume collected. Immediately after being taken, the samples were sealed with solvent rinsed aluminum foil and frozen until analysis.

Soil Core Sampler

Soil core samples were taken using an Oakfield hollow cylinder tube sampler with a 1.8 cm dia. opening (Oakfield Apparatus Co., Oakfield, WI). This type sampler was chosen because it would enclose most of the soil core within the cylinder, and thus isolate the sample as it is withdrawn from the soil, therefore minimizing sample contamination.

Soil Core Sampling Procedure--

To obtain a soil core sample, a sampling spot was randomly located in the barrel at least 10 cm away from the porous ceramic cup samplers. An open ended cylinder, 10 cm in diameter and 14 cm long, was centered over the sampling spot and slowly pushed through the zone of waste incorporation (10 cm deep). The cylinder was slowly removed, thereby, simultaneously removing a plug of the waste amended soil which was spread over the remainder of the barrel. The cylinder was then put back into the hole to prevent a cave in. A soil corer was positioned vertically in the center of the hole and slowly pushed into the soil until the tip of the corer was at a depth approximately 5 cm beyond that corresponding to the porous ceramic cup sampler. The corer was slowly withdrawn so that soil would not fall out and then laid on a piece of clean butcher paper. A 10.2 cm length of soil core was removed that corresponded to the depth at which a soil-pore water sample was taken. Thus, soil core samples were taken from between the 20 to 30 cm, 36 to 46 cm, and 53 to 64 cm depths, which corresponded to the 25 cm, 41 cm, and 61 cm deep soil-pore water samples, respectively. Immediately after sectioning, the soil core samples were transferred to a solvent washed soil moisture can, sealed with duct tape and stored in a freezer until analysis. Each time the soil corer came in contact with the soil, it

was washed with high pressure spray, scrubbed in an acetone solvent bath, and rinsed with organic-free distilled water to ensure that cross contamination of samples did not occur. After each soil core was taken, a 64 cm length of 3/4 in PVC pipe, with a rubber stopper seal at the top was pushed into the sample hole, and soil was packed around the top. The open ended cylinder was then removed and the zone of waste incorporation was carefully remixed with a hand trowel so that the waste amended soil was distributed evenly over the entire surface area. Between soil core sampling dates, the zone of waste incorporation was remixed every other week.

Soil Extraction and Analysis

To extract the organic chemicals from the soil core samples, Method 3540 (USEPA, 1982) was used with slight modification. Twenty-five g of soil from one sampling depth from one barrel was weighed into a solvent washed moisture can and mixed with 25 g of anhydrous Na_2SO_4. After being dried with Na_2SO_4, the soil core sample was put into a solvent washed cellulose extraction thimble and covered with solvent washed glass wool. The thimble was placed in either a 100 mL or 200 mL capacity Soxhlet extractor. Five solvent washed boiling stones were added to a 500 mL boiling flask containing 450 mL of a 2.33:1 dichloromethane:methanol solvent mixture. This solvent combination was used in lieu of dichloromethane alone (USEPA, 1982) because it has been shown to enhance the recovery of organic chemicals of different polarities from soils and sediments (USEPA, 1985). The Soxhlet apparatus was placed on the heater, and the temperature was set so that the 100 mL Soxhlets would cycle six times per hour and the 200 mL Soxhlets three times per hour. Preliminary extraction tests indicated that the optimum extraction time was 6 hours (Table 6). Refrigerated coolant was circulated through the condensers to optimize recovery. After extraction, the solvent extract was slowly evaporated down to approximately a 15 mL volume using a rotary evaporator. The evaporator's water bath was set at 35°C, and a minimum vacuum was used

TABLE 6. PERCENT SOLVENT EXTRACTABLE ORGANICS EXTRACTED FROM THE WPW AMENDED SAND SOIL AS A FUNCTION OF SOXHLET EXTRACTION TIME

Extraction Time (hrs)	Solvent Extractable Organics (%)
4	.036
6	.095
8	.085

to minimize chemical volatilization. The 15 mL sample was placed in a 20 ml capacity vial, and the 500 mL boiling flask was rinsed with several mL of solvent that was added to the sample. The sample was then dried through a column of solvent rinsed anhydrous Na_2SO_4, put into a clean 20 mL vial, and gently evaporated down to approximately 0.1 mL under a stream of florisil purified nitrogen. The sample was transferred to a half dram solvent washed vial and kept in a freezer until analysis. The organic chemicals of interest were identified and quantified on the GC, as previously described for the laboratory column leachate samples.

Barrel Lysimeter Waste Application

The primary goal of the barrel lysimeter study was to determine the sampling efficiency of the soil-pore water and soil core sampling systems for detecting mobile organic chemicals. However, it was also desired to use a system that would closely resemble actual land treatment facilities. Thus, waste application rates for the barrel lysimeter study were chosen to optimize chemical mobility in the soils without overloading the soils physical or biological capacity. Studies involving API separator sludge (Brown et al., 1983a) indicated that 5% (wt/wt) application rates were optimum. A 5% loading rate was also chosen for the solvent recovery sludge, although this waste is not typically land treated. Wood preservatives are designed to be toxic; therefore, the wood preserving sludge was applied at 1.5% (wt/wt) application rate to maintain some biological activity. A summary of the waste applications to the barrel lysimeters is given in Table 7.

To apply the wastes, 10 cm of soil from three barrels of the same soil type and flow rate classification (Table 5) were composited in a mixing trough. The waste needed for all three barrels was then mixed with the soil. The waste amended soil was divided evenly into thirds, and returned to the barrels.

Barrel Lysimeter Leaching Experiment

After waste application, the chemicals were leached through the soils by supplementing natural rainfall with rainwater that had been collected from a greenhouse roof and stored in a tank. Water was applied to the lysimeters on a regular time schedule to pass enough pore volumns of liquid through the soil monoliths, as suggested by the laboratory column study, to get all classes of waste constituents to migrate to at least the 61 cm sampling depth so that a complete sampling comparison could be done. The amount of water applied monthly to each soil type is given in Table 8. In order to not exceed the infiltration capacity of the loam and clay soils, and thus prevent them from becoming saturated, less water was occasionally applied to these soils. The three suction cups at the bottom of the lysimeters were kept under a continuous vacuum of about 21.3 kPa (0.213 bars), which maintained unsaturated water movement in each barrel. The volume of leachate

TABLE 7. WASTE APPLICATIONS TO BARREL LYSIMETERS

Waste	Soil	0-10 cm Soil Weight kg	Solvent Extractable Organics (%)	Application Rate (%)*	Waste Applied kg
API	Sand	39.9	5	5	39.9
	Loam	37.2	5	5	37.2
	Clay	38.7	5	5	38.7
SRS	Sand	39.9	13	5	15.4
	Loam	37.2	13	5	14.3
	Clay	38.7	13	5	14.9
WPW	Sand	39.9	34	1.5	1.77
	Loam	37.2	34	1.5	1.64
	Clay	38.7	34	1.5	1.70

* Percent by weight solvent extractable organics of the top 10 cm of soil.

collected from the suction cups was quantified and the number of pore volumes of liquid passing the 25 cm, 41 cm, and 61 cm sampling depths for the three sampling dates are given in Appendix A.

Data Quality and Validity

Care was taken throughout all areas of this study to assure the validity and quality of the data. For purposes of quality control, the study was divided into three areas: laboratory column study, field barrel lysimeters, and laboratory analysis of the samples from the former two areas. The procedures used to assure the validity of the data for each section of the study are discussed individually.

Laboratory Column Study--

This study was conducted to provide preliminary data on the mobility of the waste constituents and to guide in establishing the sampling schedule for the field barrel lysimeter study. A total of eighteen laboratory columns were run and represented duplicate columns of each of the three soils treated with three wastes. While time constraints only allowed analysis of leachate from one of each duplicate, the others were kept frozen and served as backup in case of loss or questionable analysis. The water used to leach the columns was spiked with KBr to provide a further check that the flow of a conserved anion was similar to that reported elsewhere in the literature (Goerlitz, 1984).

TABLE 8. TOTAL AMOUNT OF WATER APPLIED MONTHLY TO BARREL LYSIMETERS (RAINFALL AND IRRIGATION)

Month	Sand	Loam	Clay
	-------- Liters/Barrel --------		
Dec	6.8	8.8	6.8
Jan (1985)	12.8	12.8	10.8
Feb	27.6	27.6	27.6
Mar	41.4	25.1	28.0
Apr	39.0	39.0	33.0
May	62.6	62.6	54.6
June	57.2	55.2	47.2
July	62.9	62.9	50.9
Total	310.3	294.0	258.9

Barrel Lysimeter Study--

Since measurement of waste constituents with depth as sampled by two techniques was the primary objective of the study, care was taken to assure that all migration was through the soil. These precautions included the use of a sidewall flow barrier around the circumference of each lysimeter, and a plastic collar around each porous ceramic cup sampler. The effectiveness of these measures was determined by applying water spiked with KBr and measuring the Br concentration in the leachate collected from the three suction cups in the bottom of each lysimeter. Three replications of each treatment were run to allow for variability within each soil.

Chemical Analysis--

Details of the chemcial analysis procedures and instrument conditions are presented in the leachate chemical analysis section. Quality assurance involved calibrating the gas chromatograph twice daily which corresponded to an average of once per 5 samples and never more than once per 10 samples. Each unknown was spiked with a known quantity of internal standard. All solvents were analyzed for purity prior to use. Control samples using all procedures, solvents, etc., except for an unknown, were used to check for contamination and/or interferences.

Statistical Evaluation of Data--

The primary objective of the study was to compare the ability of porous ceramic cups and soil cores to sample mobile organic waste constituents in unsaturated soil. The data consisted of a large number

of paired values of chemical concentrations from both sample types. A paired t test of the pairs and a regression analysis with the soil-pore water concentration as the dependent variable were conducted.

SECTION 5

RESULTS AND DISCUSSION

LABORATORY SOIL COLUMN STUDY

Bromide Breakthrough Curves

The water used to leach the waste constituents through the soil columns contained a bromide spike, thus providing a means of directly comparing the relative adsorption and mobility of the organic chemicals of interest against the nonadsorbed bromide ion. The bromide breakthrough curves were very consistent between the various soil-waste treatments with the effluent bromide concentration (C) reaching the influent bromide concentration (C_o), typically at 1.4 pore volumes (Figure 3). Early bromide breakthrough was not observed on any of the columns which indicated that there was no preferential sidewall flow.

The dispersion transport characteristics of each soil were evaluated by fitting the breakthrough data to the following form of the chromatographic equation for one dimensional transport of a conserved anion as suggested by Goerlitz (1984):

$$C/Co = 1/2 \text{ erfc} \left\{ \frac{L-(q/\theta)t}{2\sqrt{(D/\theta)t}} \right\} + 1/2 \exp \left(\frac{(q/\theta)L}{D/\theta} \right) \text{erfc} \left\{ \frac{(L+(q/\theta)t}{2\sqrt{(D/\theta)t}} \right\}$$

where: C = Br^- concentration of effluent, mg L^{-1}
C_o = Br^- concentration of influent, mg L^{-1}
D = dispersion coefficient, cm^2 sec^{-1}
erfc = complimentary error function, (1-erf)
exp = exponent, base e
q = water flux, cm sec^{-1}
θ = porosity, (fraction percent, i.e. 0.46)
t = time, sec
L = soil column length, cm

By rearranging so that D is the only unknown in the equation, the following is obtained:

$$C/Co = 1/2 \text{ erfc} \left\{ \frac{\theta L - qt}{2\sqrt{D\theta t}} \right\} + 1/2 \exp \left(\frac{(qL)}{D} \right) \text{erfc} \left\{ \frac{\theta L + qt}{2\sqrt{D\theta t}} \right\}$$

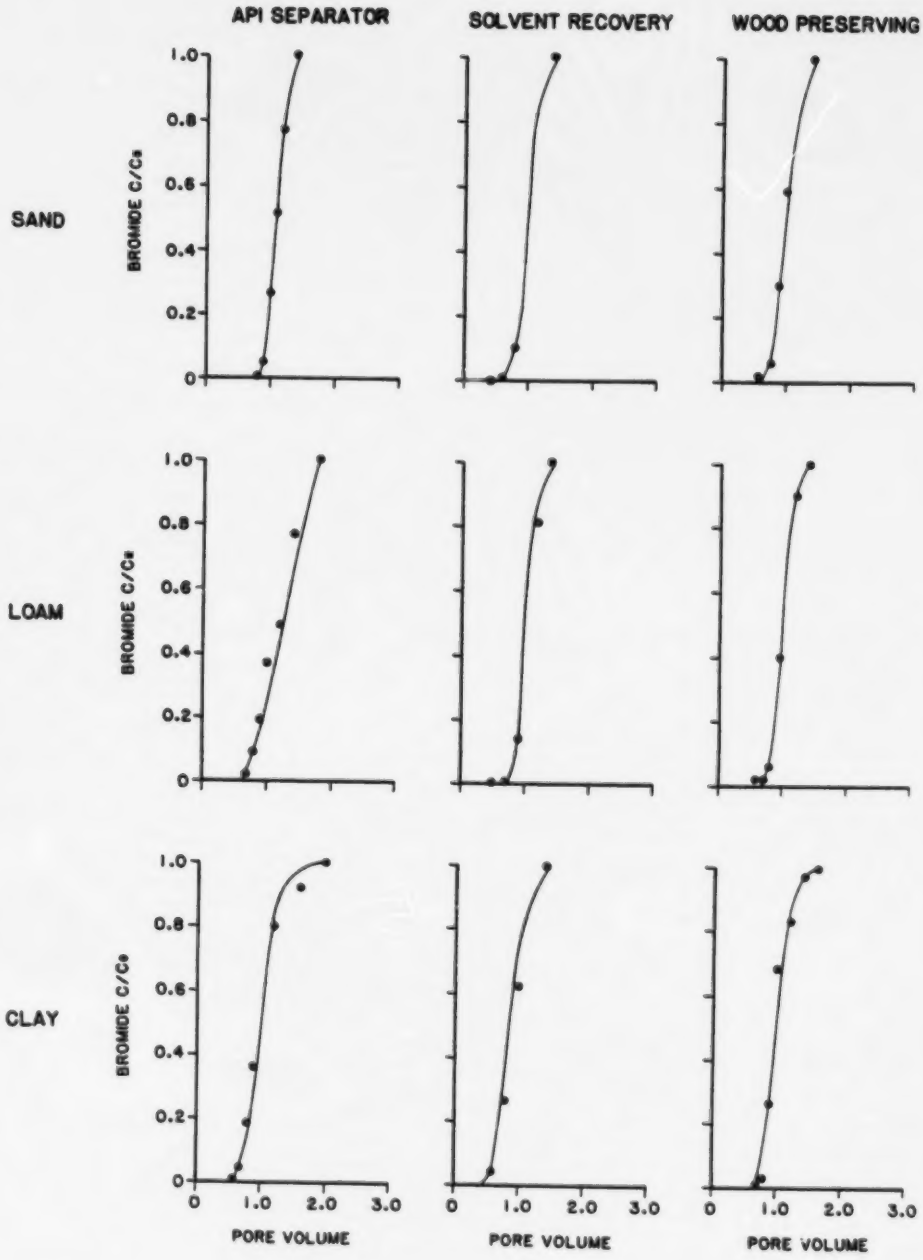

Figure 3. Actual (●) versus calculated (—) breakthrough of Br^- from laboratory columns of three soils treated with API separator, solvent recovery, and wood preservative wastes.

The dispersion coefficients (D) were adjusted until the calculated Br^- breakthrough curve was obtained that closely fit the actual data. The Br^- breakthrough curves for the laboratory columns of the three soils and three wastes are given in Figure 3. The laboratory soil column transport equation parameters are given in Table 9. The dispersion coefficients for the soils are within the anticipated range based on the data for (Goerlitz, 1984). All the fitted curves pass very near C/Co of 0.5 at one pore volume, which according to theoretical calculations, indicates that the soils behaved like homogenous porous media.

TABLE 9. LABORATORY SOIL COLUMN TRANSPORT EQUATION PARAMETERS FOR BROMIDE

Waste	Soil	Dispersion Coefficient (D) ($cm^2\ s^{-1}$)	Water Flux (q) ($cm\ s^{-1}$)	Porosity	Soil Column Length (cm)
API	Sand	6.0×10^{-5}	2.65×10^{-4}	0.435	28
	Loam	1.3×10^{-4}	3.52×10^{-5}	0.469	28
	Clay	2.9×10^{-5}	4.17×10^{-5}	0.428	28
SRS	Sand	3.4×10^{-4}	9.05×10^{-4}	0.432	28
	Loam	4.0×10^{-5}	1.46×10^{-4}	0.477	28
	Clay	8.0×10^{-5}	1.19×10^{-4}	0.428	28
WPW	Sand	6.0×10^{-5}	1.47×10^{-4}	0.413	28
	Loam	1.5×10^{-5}	5.77×10^{-5}	0.468	28
	Clay	2.4×10^{-5}	5.78×10^{-5}	0.421	28

Organic Chemical Breakthrough Curves

Breakthrough curves for alkanes from the API waste leached through the clay textured Bastrop soil are given in Figure 4. Hydrocarbons having 16 to 29 carbon atoms were found to occur in the leachate at 1 to 2 pore volumes. For compounds having 16 to 27 carbons (Figure 4a to 4c), concentrations remained less than 0.4 $\mu g\ L^{-1}$, while compounds having 28 and 29 carbons reached concentrations up to 4 $\mu g\ L^{-1}$ (Figure 4d). Distinct concentration peaks were generally reached at 2 pore volumes of leachate. Results for the sand textured Padina soil were similar and are shown in Figure 5. However, concentrations of alkanes in the leachate ranged up to 11 $\mu g\ L^{-1}$ which is almost three times higher than what was found in the clay soil leachate. Likewise, whereas there were distinct breakthrough peaks for the clay soil, in the sand soil there appeared to be bursts of chemical breakthrough, with continued release of alkanes even after eight pore volumes of leachate had been collected. This data indicates the increased adsorption of

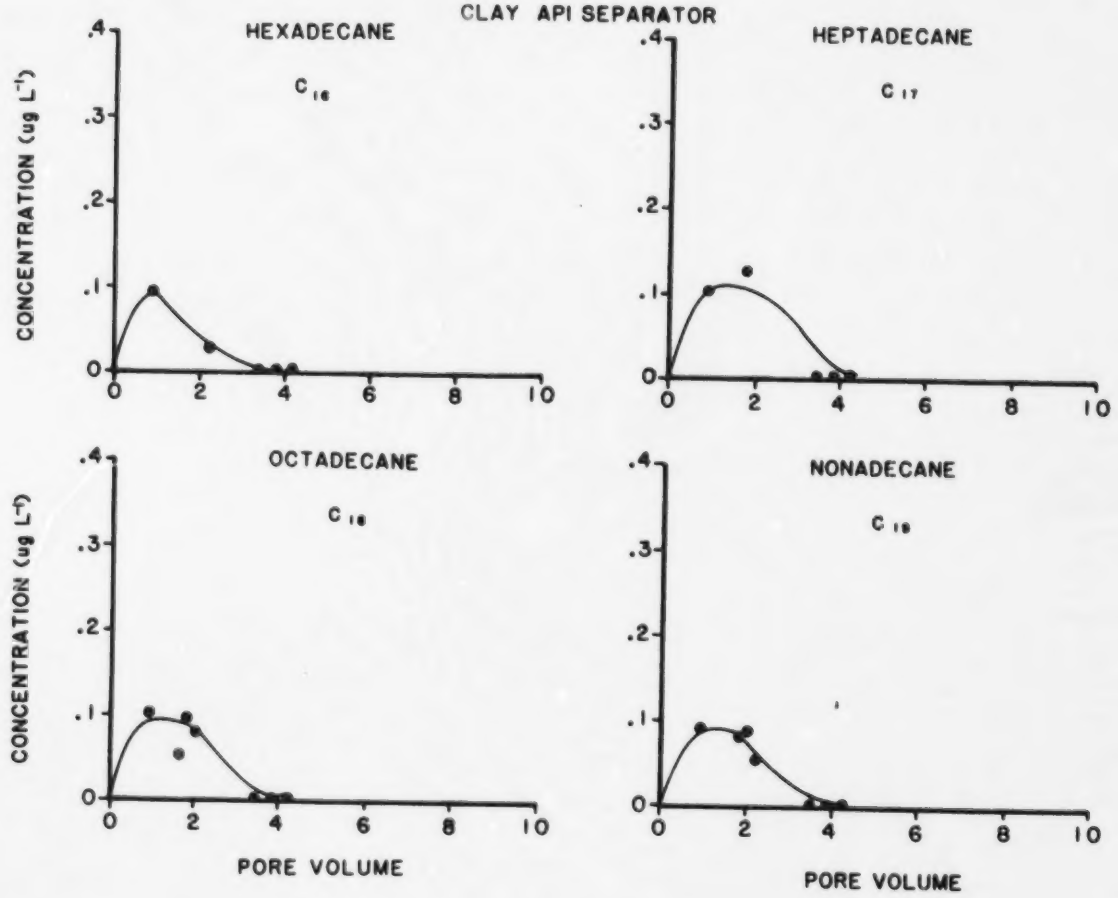

Figure 4a. Breakthrough of hexadecane, heptadecane, octadecane, and nonadecane from laboratory columns of clay soil treated with API separator sludge.

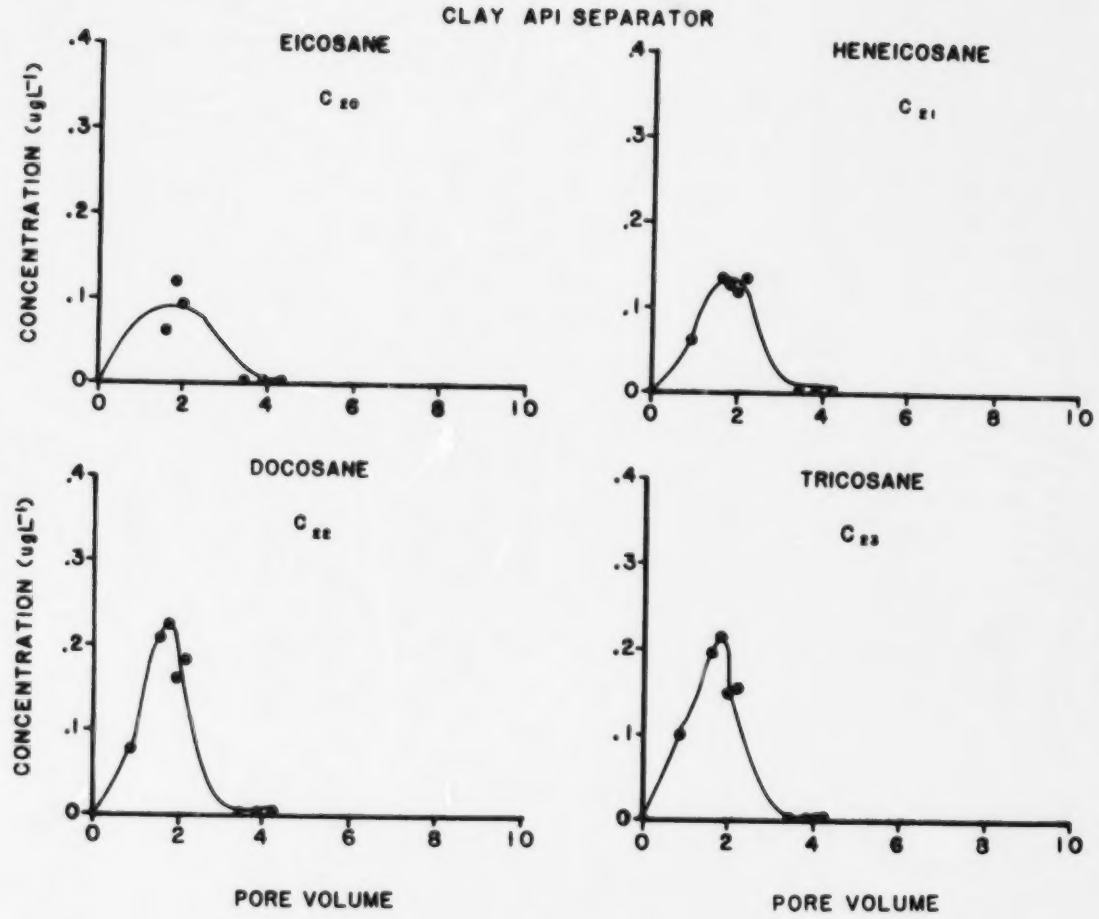

Figure 4b. Breakthrough of eicosane, heneicosane, docosane, and tricosane from laboratory columns of clay soil treated with API separator sludge.

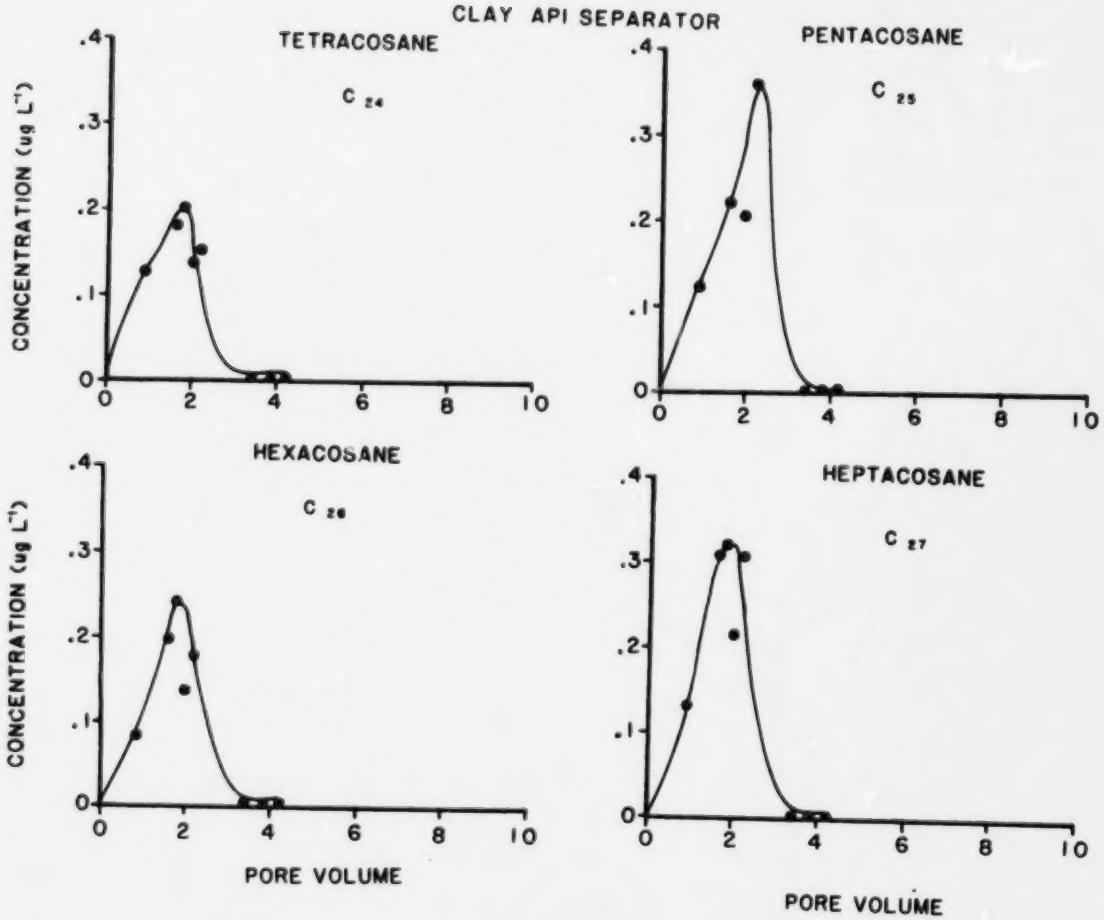

Figure 4c. Breakthrough of tetracosane, pentacosane, hexacosane, and heptacosane from laboratory columns of clay soil treated with API separator sludge.

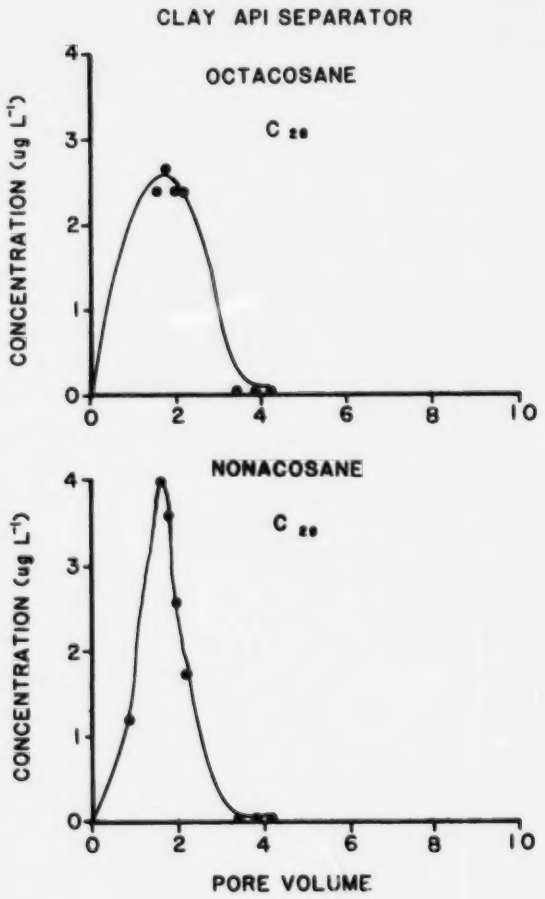

Figure 4d. Breakthrough of octacosane and nonacosane from laboratory columns of clay soil treated with API separator sludge.

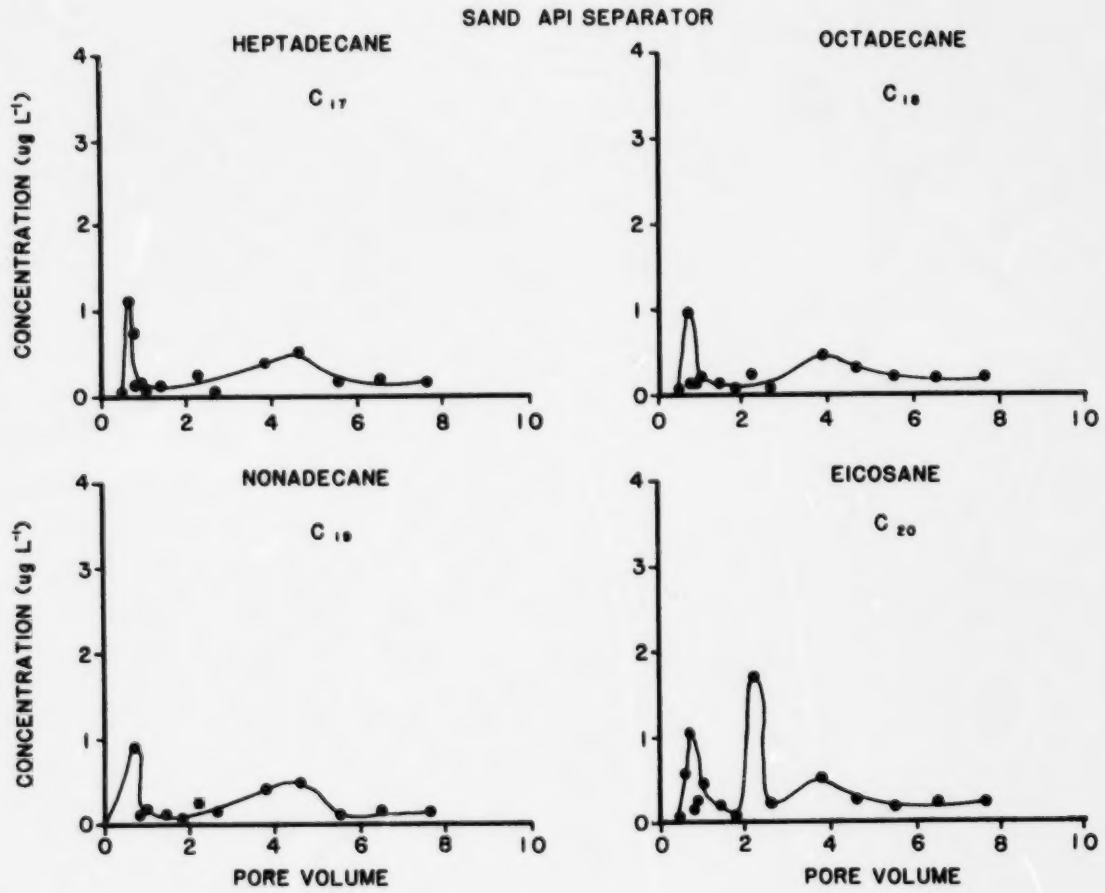

Figure 5a. Breakthrough of heptadecane, octadecane, nonadecane, and eicosane from laboratory columns of sand soil treated with API separator sludge.

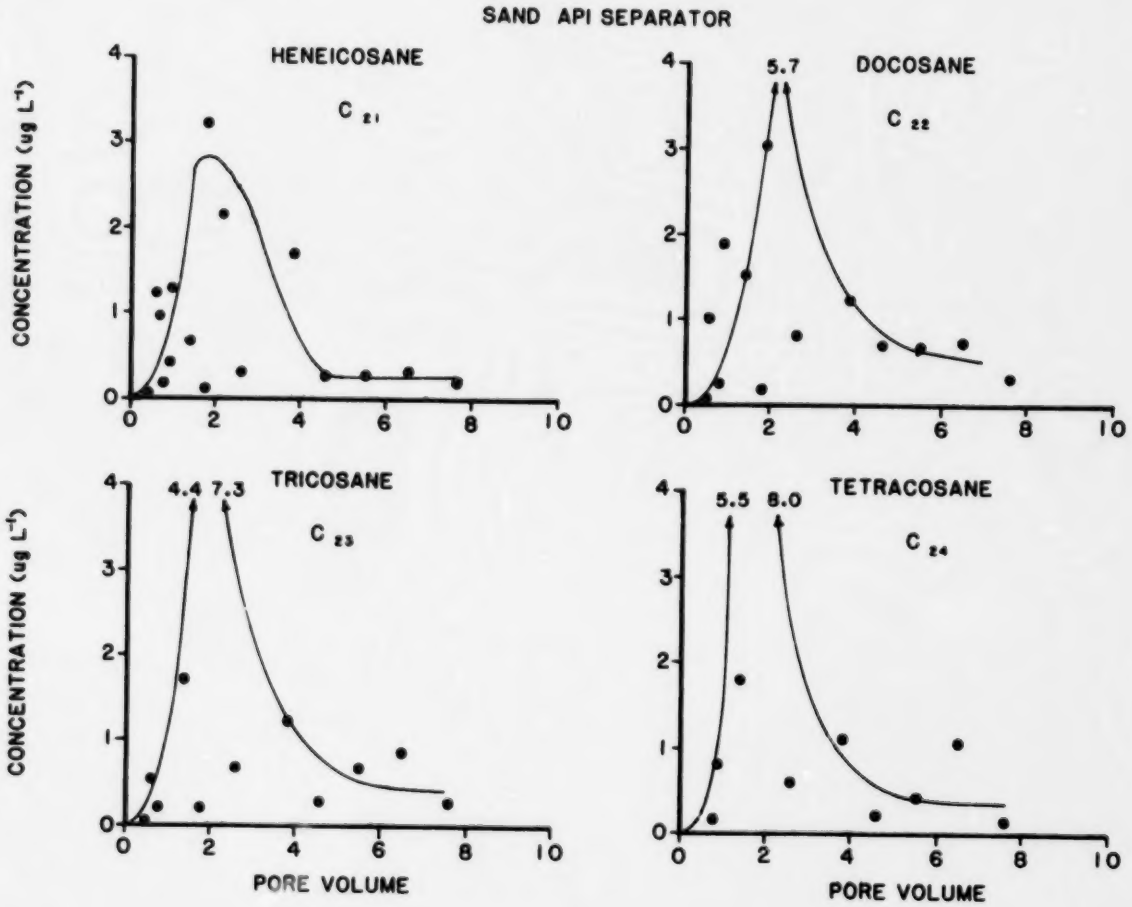

Figure 5b. Breakthrough of heneicosane, docosane, tricosane, and tetracosane from laboratory columns of sand soil treated with API separator sludge.

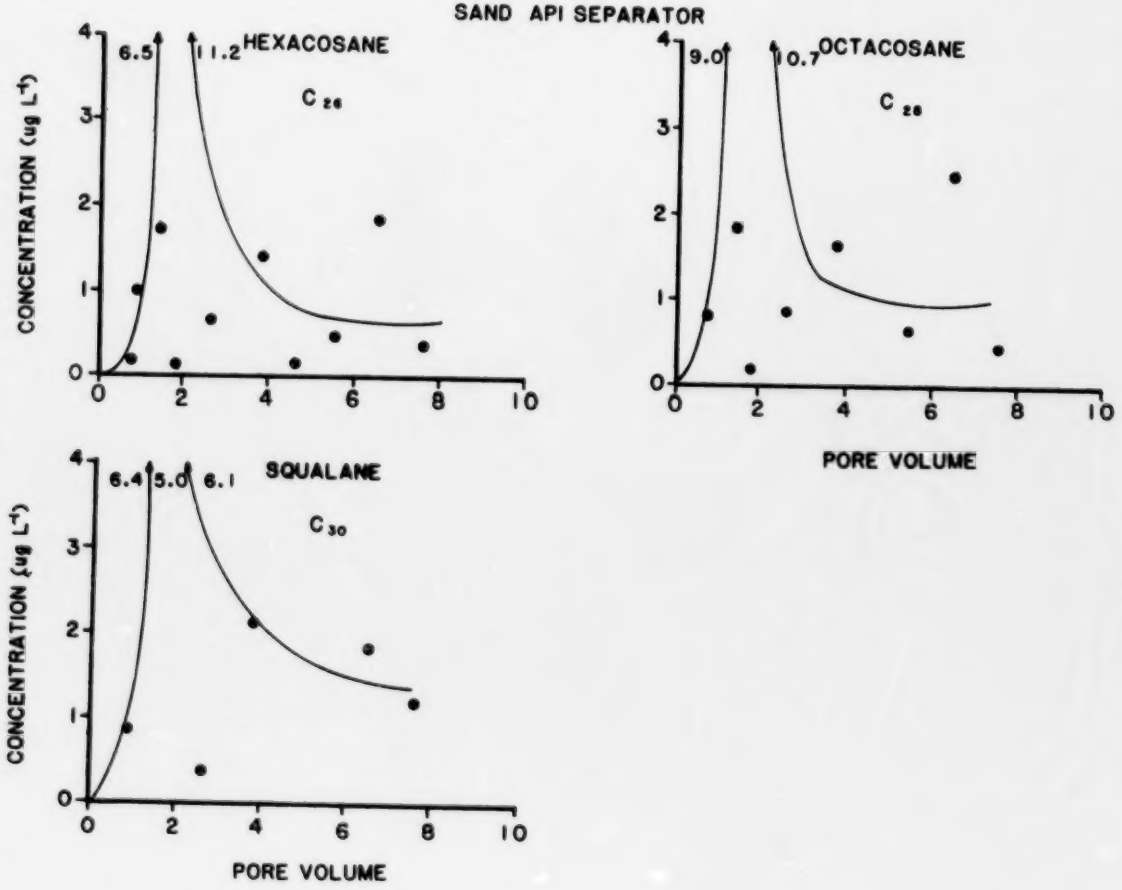

Figure 5c. Breakthrough of hexacosane, octacosane, and squalane from laboratory columns of sand soil treated with API separator sludge.

alkanes in the clay soil, due possibly to a higher organic carbon content, which would strongly adsorb the alkanes, and/or adsorption onto the clay minerals.

The compounds identified and shown in Figures 4 and 5 are all straight chain hydrocarbons belonging to the alkane family and have the general formula of C_nH_{2n+2}. As a group, these chemicals are non-polar; less dense than water; insoluble in water, dilute acids, dilute bases, or concentrated H_2SO_4; and unreactive to most chemicals. Alkanes with 5 to 17 C atoms are liquids (22°C) while those having more than 17 C atoms are solids. The non-polar nature and insolubility of the alkanes causes them to be partitioned out of the water phase and thus be adsorbed to the soil, which explains their low concentrations in the aqueous leachate. However, those alkanes that did dissolve in water behaved much like the bromide anion indicating that they were unreactive to the adsorptive surfaces of the soil particles.

While this experiment was not designed to provide a mass balance of the different compounds, an estimation was made of the percentage of applied alkanes found in the leachate. Of the soils treated with the API waste, the highest alkane concentration in the leachate was from hexacosane in sandy soil (Figure 5c). The peak concentration reached 11.2 μg L^{-1}. Assuming that this concentration was maintained from the first to third pore volumes (0.4 L) would mean that 4.5 μg were lost (11.2 μg L^{-1} x 0.4 L). The concentration of hexacosane in the waste was 0.7 mg g^{-1} (Table 10) and 34.5 g of waste was applied to

TABLE 10. AVERAGE CONCENTRATION OF ALKANES IN API SEPARATOR SLUDGE

	mg g^{-1}
Hexadecane	5.3
Heptadecane	5.4
Octadecane	3.4
Nonadecane	4.0
Eicosane	2.8
Heneicosane	2.0
Docosane	1.7
Tricosane	1.4
Tetracosane	1.0
Pentacosane	1.0
Hexacosane	0.7
Heptacosane	0.5
Octacosane	1.5
Nonacosane	3.7

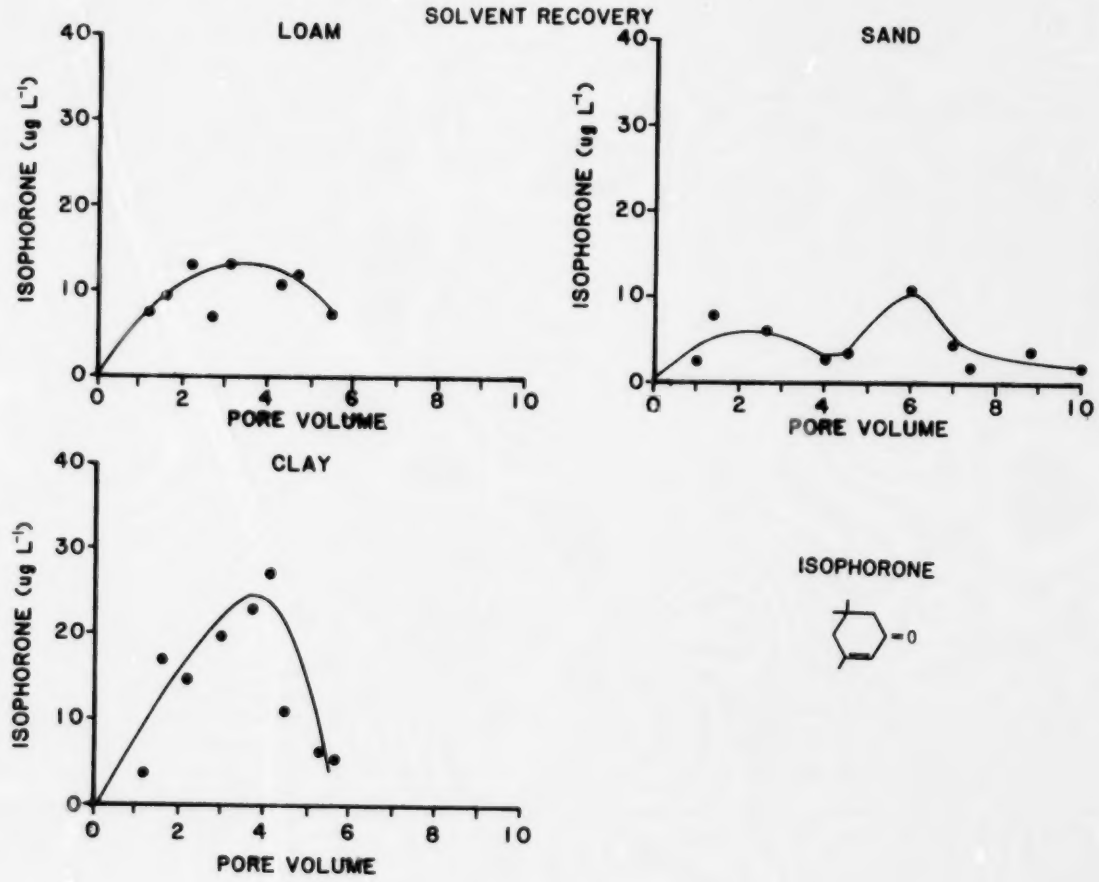

Figure 6. Breakthrough of isophorone from laboratory columns of sand, loam, and clay soil treated with solvent recovery sludge.

each column; thus 2.4×10^4 µg of hexacosane was applied. Therefore, as a "worst case" estimate, only approximately 0.02% of the applied hexacosane was lost in the leachate and the remainder was retained in the column or degraded. Therefore, in the field lysimeter phase, peak concentrations of alkanes may represent only approximately 0.02% of that applied and should be anticipated at 2 pore volumes.

The solvent recovery sludge contained a host of organic compounds but the predominant compound was isophorone. Due to the limited scope of the laboratory portion of this work, concentrations of only isophorone in the leachate were followed (Figure 6). A clear breakthrough curve was measured for the clay soil with the peak concentration of about 28 µg L^{-1} occurring at 4 pore volumes of leachate. The loam soil exhibited a similar curve however it was lower in concentration and spanned a greater pore volume. The sand column did not give a clear breakthrough curve. The physical properties of the solvent waste appeared to have an affect on the permeability of all three soils. The water flux in the soils was consistently almost an order of magnitude greater than in soils treated with the API separator and wood preserving wastes (Table 9). It is likely that the solvents caused a change in the pore-size distribution thereby producing larger pores through which liquid may move. Such changes have been reported by Anderson *et al.* (1985) and Brown (1985) for soils permeated with organic solvents. For the field lysimeter study, isophorone breakthrough should be expected at about 4 pore volumes.

The wood preservative waste contained thirteen compounds which were traced in the laboratory study. Concentrations of constituents in wood preservative waste leached through the clay textured Bastrop soil are given in Figure 7. Of the thirteen compounds, 2,4-dimethylphenol and pentachlorophenol were the major constituents found in the leachate. The 2,4-dimethylphenol breakthrough curve exhibited a maximum concentration of 4200 µg L^{-1} occuring at 3 pore volumes. Pentachlorophenol on the other hand behaved quite differently and did not appear until after about the fourth pore volume of leachate after which it steadily increased until by the passage of 10 pore volumes it reached a concentration of 9000 µg L^{-1}. Concentrations of phenanthrene and anthracene in the leachate remained below 2 µg L^{-1} and peaked at 3 pore volumes. Acenaphthene behaved similarly to phenanthrene and anthracene initially, but later had increased movement, even after 12 pore volumes of leachate had been collected. Concentrations of fluorene remained below 0.5 µg L^{-1} and appeared at 5 to 6 pore volumes of leachate. Pyrene in the leachate exhibited a peak concentration of 1.3 µg L^{-1} at 1 pore volume of leachate and decreased to zero after 2 pore volumes.

Concentrations of constituents in wood preservative waste leached through the loam textured Norwood soil are given in Figure 8. Pentachlorophenol was the most predominant constituent and reached a maximum concentration of 1500 µg L^{-1} at 6 pore volumes of leachate.

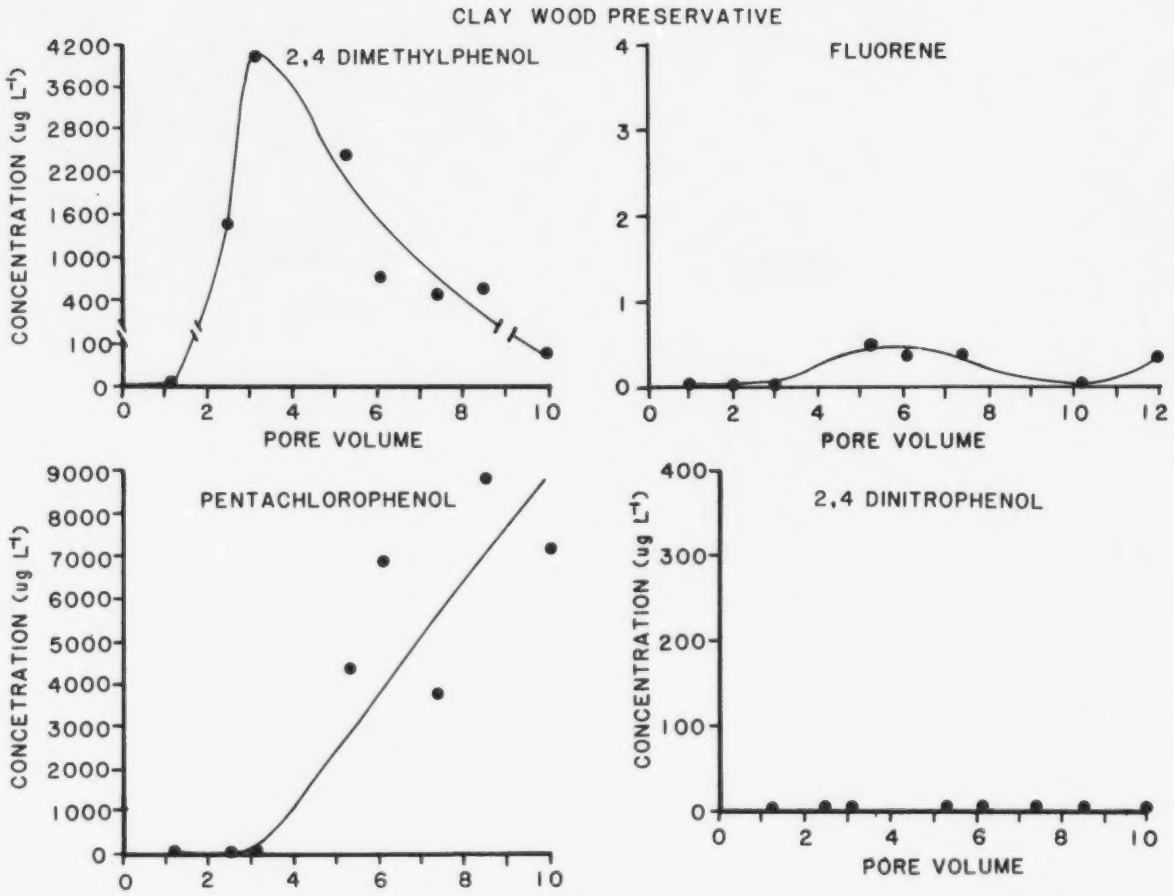

Figure 7a. Breakthrough of 2,4 dimethylphenol, pentachlorophenol, 2,4 dinitrophenol, and fluorene from laboratory columns of clay soil treated with wood preservative waste.

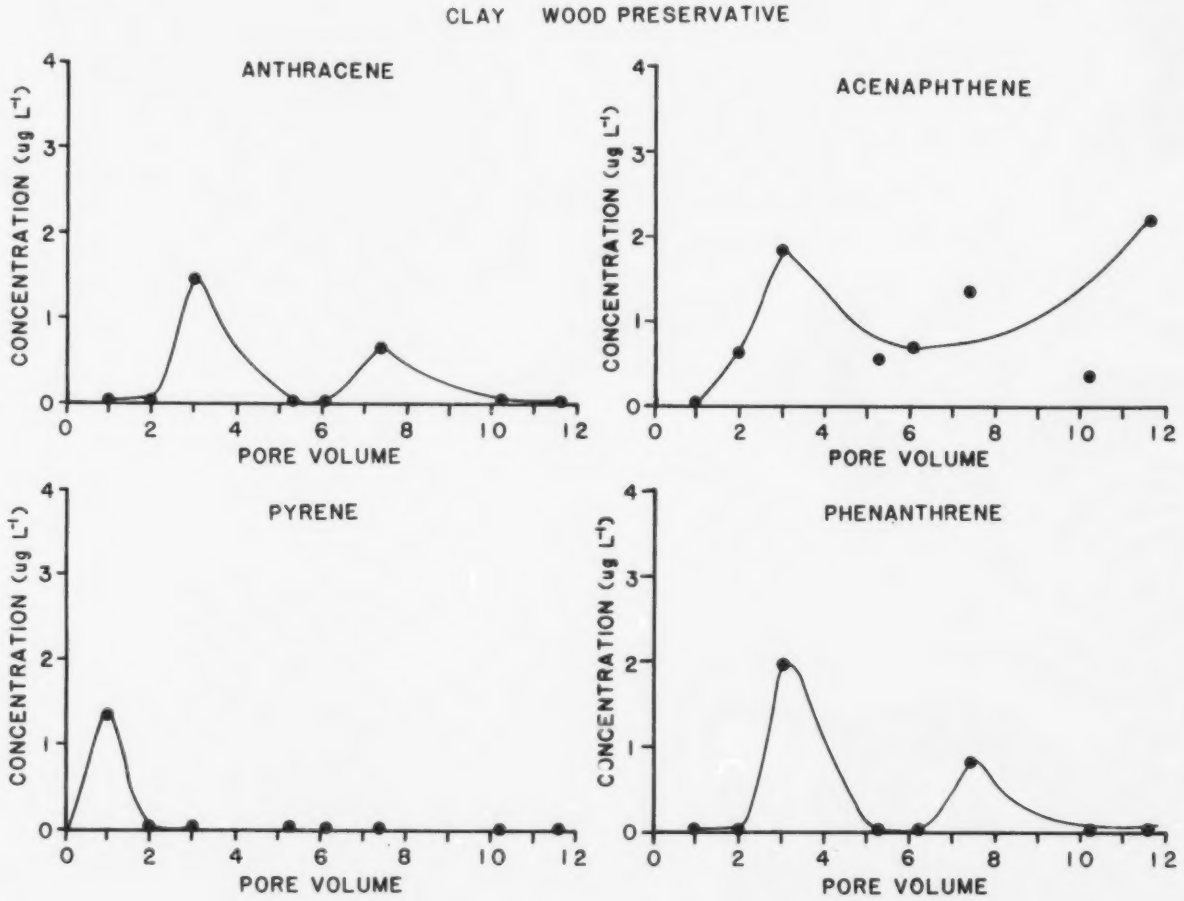

Figure 7b. Breakthrough of anthracene, acenaphthene, phenanthrene, and pyrene from laboratory columns of clay soil treated with wood preservative waste.

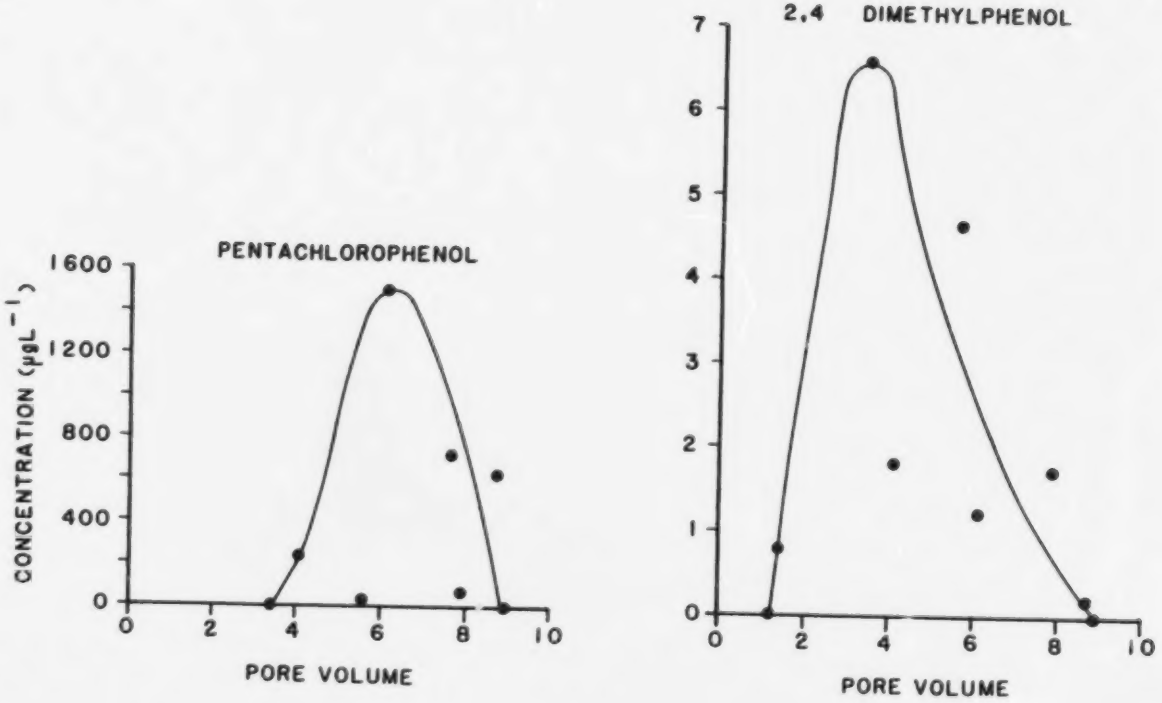

Figure 8a. Breakthrough of pentachlorophenol and 2,4 dimethylphenol from laboratory columns of loam soil treated with wood preservative waste.

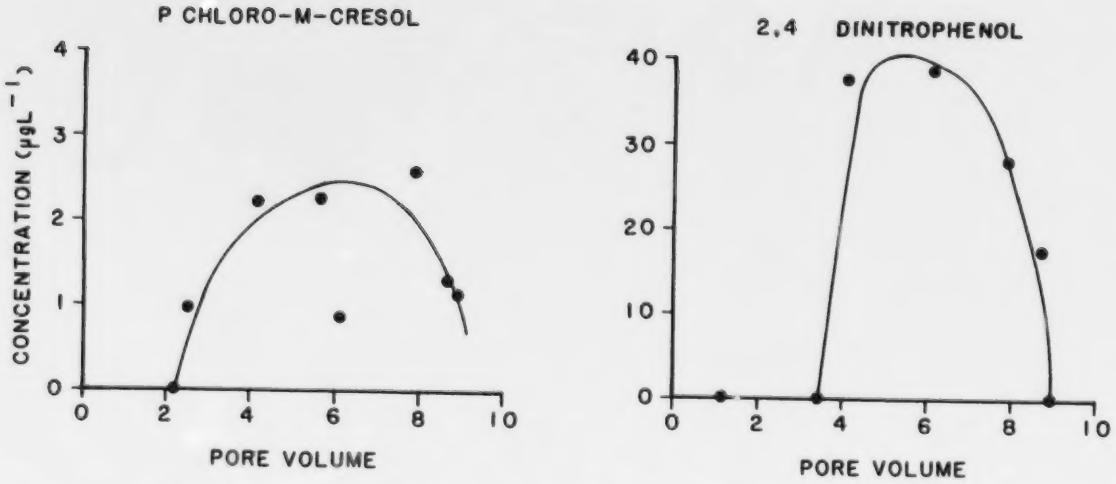

Figure 8b. Breakthrough of p-chloro-m-cresol and 2,4 dinitrophenol from laboratory columns of loam soil treated with wood preservative waste.

In contrast to the 4200 µg L^{-1} concentration of 2,4-dimethylphenol detected in the leachate from the clay, only 6.5 µg L^{-1} were found in the leachate from the loam soil. Peak concentrations, however, did occur after 3 pore volumes as in the clay soil. Concentrations of 2,4-dinitrophenol in the leachate from the loam soil amended with wood preservative peaked at 40 µg L^{-1} by the passage of 4 pore volumes. Concentrations of p-chloro-m-creosol peaked at 2.5 µg L^{-1} at 6 pore volumes of leachate.

Concentrations of pentachlorophenol in the leachate from the sand textured soil amended with wood preservative waste began increasing at 4 pore volumes of leachate and increased throughout the experiment (Figure 9a). The highest concentrations measured were 2500 µg L^{-1}. The shape of the breakthrough curve for 2,4-dimethylphenol in the sand (Figure 9a) was similar to that from the clay soil (Figure 7a) even though the peak concentration was lower in the sand. A peak concentration of approximately 200 µg L^{-1} was reached at about 2 and 5.5 pore volumes and decreased thereafter. Two peaks of 2,4-dinitrophenol were evident in the leachate from the sand. The first peak was 175 µg L^{-1} at 1 pore volume and the second peak was 100 µg L^{-1} at 6.5 pore volumes. Concentrations of anthracene, phenanthrene and pyrene in the leachate from the sand all remained well below 1 µg L^{-1} (Figure 9b). Concentrations of both fluorene and acenaphthylene began to increase at 3 pore volumes. Fluorene reached only 1 µg L^{-1} by the passage of 10 pore volumes of leachate. Acenaphthylene, however, rose to 90 µg L^{-1} by 10 pore volumes.

In general it appears that pentachlorophenol, 2,4-dimethylphenol, 2,4-dinitrophenol, and acenaphthylene are the major constituents to be leached from wood preservative waste amended soils. Waste constituents appear in the leachate at pore volumes from 1 to 10 and will require an extensive sampling schedule in the field lysimeters.

BARREL LYSIMETER STUDY

API Treated Lysimeters

Concentrations of alkanes and polynuclear aromatics (PNA's) in the soil core and soil-pore water samples are given in Appendix B. The greatest number of samples having a measurable concentration of the chemicals studied were in the sand lysimeters followed by the clay and lastly the loam lysimeters. The large number of samples containing waste contituents collected from the sand lysimeters indicates that the waste constituents were most mobile in this soil. This is likely due to the low organic carbon, clay content, and cation exchange capacity of this soil. The sand soil being unstructured, had a more uniform pore-size distribution and lacked cracks and large interped pores. Thus, it may have been a more suitable media for the pore samplers to collect a representative sample.

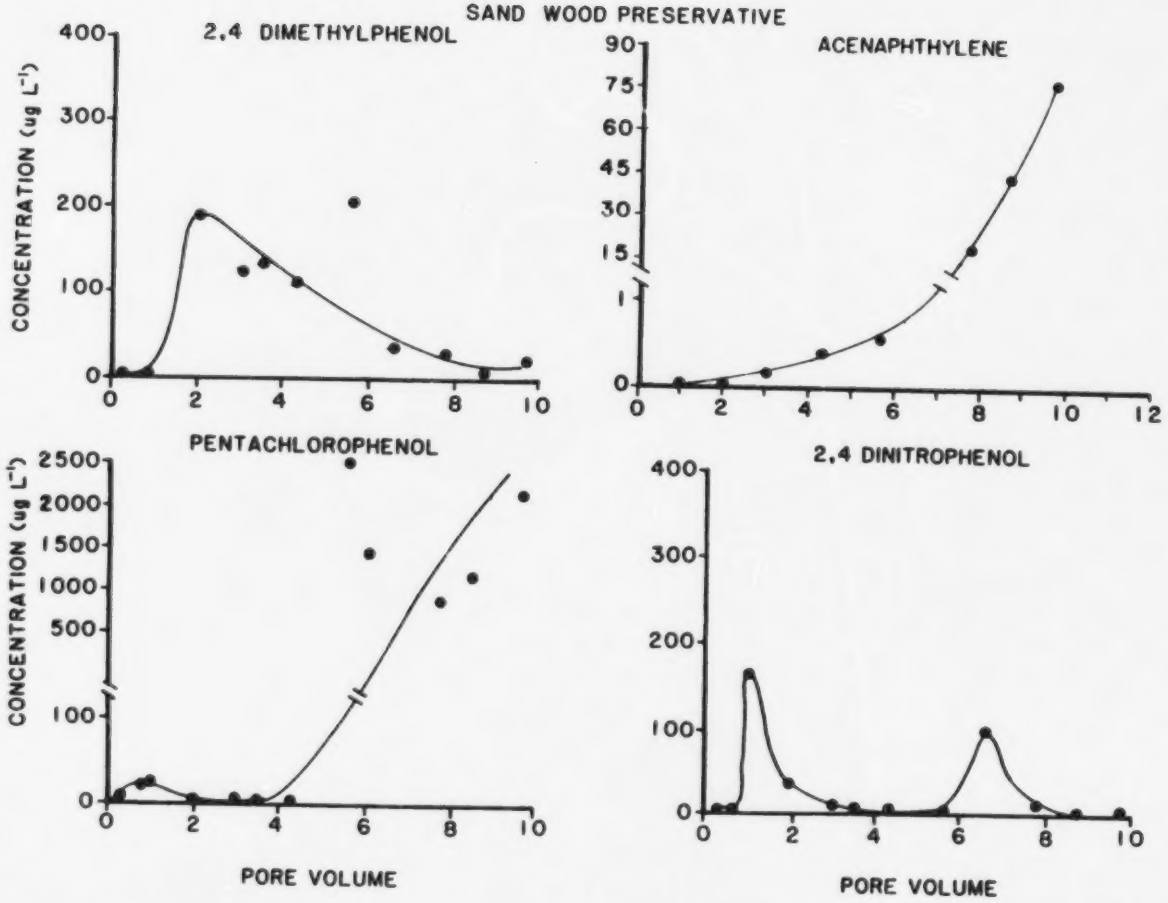

Figure 9a. Breakthrough of 2,4 dimethylphenol, pentachlorophenol, 2,4 dinitrophenol, and acenaphthylene from laboratory columns of sand soil treated with wood preservative waste.

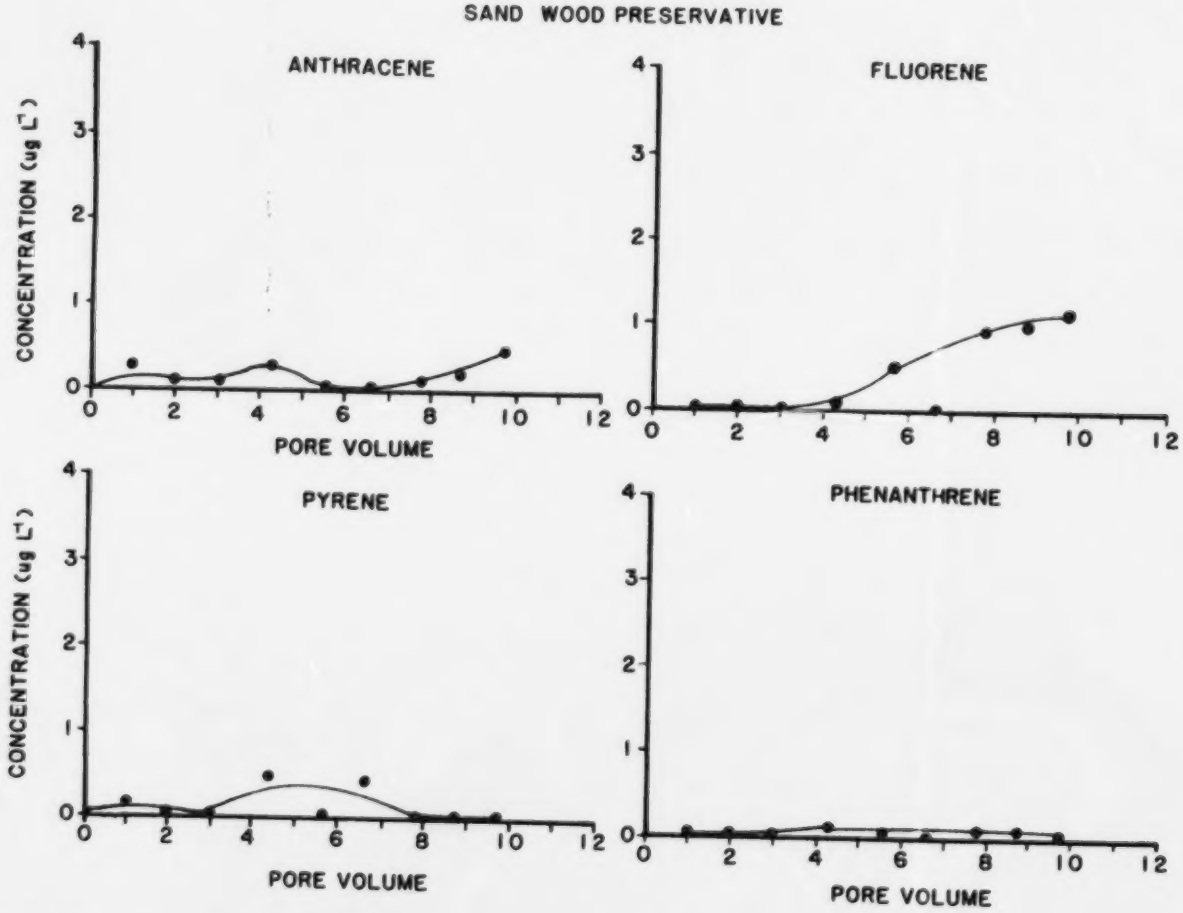

Figure 9b. Breakthrough of anthracene, fluorene, phenanthrene, and pyrene from laboratory columns of sand soil treated with wood preservative waste.

Waste constituents were generally detected in either the pore water or core sample but rarely in both samples taken at the same time and location. Table 11 lists the percentage of samples containing measureable quantities of each alkane that occurred in pore water or

TABLE 11. THE PERCENTAGE OF SAMPLES FROM THREE SOILS HAVING A MEASURABLE QUANTITY OF EACH ALKANE THAT OCCURRED IN EITHER THE SOIL CORE SAMPLE ONLY, PORE WATER SAMPLE ONLY, OR BOTH

Chemical	Log K_{ow}	Soil Core	Pore Water	Both
		(%)		
Nonane	4.51	17	83	0
Decane	5.01	11	89	0
Undecane	5.58	55	40	5
Dodecane	6.10	31	54	15
Tridecane	6.65	50	29	21
Tetradecane	7.20	75	25	0
Pentadecane	7.72	87	9	4
Heptadecane	8.25	96	0	4
Nonadecane	8.79	94	3	3
Tricosane	12.00	100	0	0
Tetracosane	12.53	91	9	0

core samples or both. Of the samples containing measurable amounts of nonane and decane, 83 and 89%, respectively, were found in the soil-pore water samples. The next three larger alkanes, undecane, dodecane, and tridecane occurred 55, 31 and 50% of the time, respectively, in the soil core samples. The remaining alkanes, those heavier than tridecane, occurred from 75 to 100% of the time in the soil core samples. A statistical comparison of the alkane concentrations measured in the soil and soil-pore water is given in Appendix C. In general, the data were variable and the standard deviation often equalled or exceeded the mean. For the sand, significant differences between soil core and soil-pore water concentrations were only found for heptadecane and nonadecane. For the loam soil, significant differences were observed for undecane and nonadecane. In the clay soil only decane and nonadecane differed significantly. In general, the regression analyses indicated little correlation between core and pore water samples. Only for tetradecane, heptadecane and nonadecane in the clay soil, were the r^2 values above 0.6 indicating some degree of relationship.

A trend in the data can be observed. For mean concentrations of decane, undecane, dodecane and tridecane, the chemical concentration in the soil-pore water tends to exceed that of the soil samples, while

for all the heavier alkanes, tetradecane to tetracosane, the inverse is true and the concentrations in the soil exceed those in the pore water. Thus, it appears that soil-pore water sampling would be preferable to monitor the movement of alkanes having 10 or fewer carbons, while soil core samples would be best for monitoring alkanes with greater than 10 carbons.

PNA compounds occurred almost exclusively in soil core samples with phenanthrene as a single exception (Table 12). Very rarely were PNA's detected in both soil core and soil-pore water samples from a given location.

TABLE 12. THE PERCENTAGE OF SAMPLES FROM THREE SOILS HAVING A MEASURABLE QUANTITY OF EACH PNA THAT OCCURRED IN EITHER THE SOIL CORE SAMPLE ONLY, PORE WATER SAMPLE ONLY, OR BOTH

Chemical	Log K_{ow}	Soil Core	Pore Water	Both
		(%)		
Acenaphthene	3.92	96	2	2
Acenaphthylene	4.07	100	0	0
Fluorene	4.18	98	0	2
Phenanthrene	4.46	89	11	0
Anthracene	4.54	100	0	0
Pyrene	5.18	98	2	0
Fluoranthene	5.33	97	0	3
Chrysene	5.79	100	0	0

A statistical evaluation of the data (Appendix C) showed that for the sand, concentrations of acenaphthylene, acenaphthene, fluorene, fluoranthene and pyrene were significantly higher in the soil samples. All soil-pore water samples from the sand textured soil averaged less than 1 $\mu g\ L^{-1}$ as compared to averages as high as 36 $\mu g\ kg^{-1}$ in the soil samples. In the loam textured soil, concentrations of acenaphthylene, anthracene, and chrysene were significantly greater in the soil samples. All soil-pore water samples from the loam averaged less than one $\mu g\ L^{-1}$ as compared to 1.5 to 8.2 $\mu g\ kg^{-1}$ from the soil core samples. In the clay soil, only concentrations of acenaphthene and anthracene were significantly greater in the soil core samples and all others were similar. More compounds were measurable in the soil-pore water in the clay soil than in either of this other soils. This may be due in part to flow through large pores between structural units in the soil. Variability in all concentration data from both soil core and soil-pore water samples was high and regression analyses showed very poor correlations. Only fluoranthene in the clay soil showed a

high r^2 of 0.93. This was likely due to the small number of data points (n = 4) and the small spread of data (3 points between 1-2 µg kg^{-1}). With additional data, the correlation would be expected to decrease.

An evaluation of the log K_{ow} for PNA's indicates a range of 3.92 to 5.79. Chemicals with log K_{ow} values in this range would be expected to be partitioned onto the soil fraction. Therefore, it follows that the soil core sampling technique was best for detecting these compounds since they are associated with the soil matrix and are not sampled well by soil-pore water samplers. Several investigators, as reported by Dzombak and Luthy (1984), have found that PNA adsorption in soils is highly correlated with the K_{ow} of the chemical and the fraction organic carbon content (OC) of the soil. Thus, the partitioning of PNA's between water and soil (Kp) can be predicted (r^2 = 0.98) by the relationship:

$$Kp = 0.482 (K_{ow}) (OC)$$

thus, in a soil having 0.95% organic carbon (OC = 0.0095), a PNA having a K_{ow} of $10^{4.46}$ would have a Kp of 132, which indicates that the chemical would tend to be adsorbed on the soil. Therefore, it is reasonable that soil core samples are more efficient than soil-pore water samples for PNA compounds.

WPW Treated Lysimeters

Concentrations of phenols and cresols in the soil core and soil-pore water samples are given in Appendix D. Mobile constituents from the WPW were detected in both the soil core and pore water samples (Table 13). By arranging these chemicals according to their log K_{ow}, from lowest to highest (Table 13), it appears that these compounds with log K_{ow} values in the 1.5 to 3.4 range were weakly adsorbed to the soil and thus are fairly randomly sampled by both soil core and soil-pore water techniques. Pentachlorophenol would tend to be more strongly adsorbed to the soil, and thus appeared to be better sampled by taking a soil core sample.

Due to the limited number of times that measurable quantities of wood preservative waste constituents were detected, statistical comparisons could only be done for 4,6-dinitro-o-cresol in all soils, pentachorophenol in the loam and 2,4,6-trichlorophenol in the sand (Appendix E). In all cases, no significant differences were found between the average concentration in the soil core or soil-pore water. The data were variable with standard deviations as large as the mean. A regression analysis of the concentration of 4,6-dinitro- o-cresol in the clay soil had a very poor correlation indicating a lack of relationship between the two measurements.

TABLE 13. THE PERCENTAGE OF SAMPLES FROM THREE SOILS HAVING A MEASURABLE QUANTITY OF EACH WPW CONSTITUENT THAT OCCURRED IN EITHER THE SOIL CORE SAMPLE ONLY, PORE WATER SAMPLE ONLY, OR BOTH

Chemical	Log K_{ow}	Soil Core (%)	Pore Water (%)	Both (%)
Phenol	1.46	50	50	0
2,4 dinitrophenol	1.53	75	25	0
2-nitrophenol	1.76	50	50	0
4-nitrophenol	1.91	0	0	0
2-chlorophenol	2.17	0	0	0
2,4 dimethylphenol	2.5	67	33	0
2,4 dichlorophenol	2.75	100	0	0
4,6 dinitro-o-cresol	2.85	88	7	7
p-chloro-m-cresol	2.95	0	100	0
2,4,6 trichlorophenol	3.38	14	86	0
Pentachlorophenol	5.01	75	25	0

SRS Treated Lysimeters

Constituents of the SRS waste were weakly adsorbed to the soils as evidenced by their rapid movement in significant quantities through all three soils (Appendix F). Twenty days after waste application, chemicals in concentrations greater than 20 mg L^{-1} were found in both the soil core and soil-pore water samples at the 61 cm depth. In another field study, Barbee and Brown (1986b) found that xylene moved to the 61 cm depth in 0.5 hr, 1 hr and 1 day in undisturbed clay, loam and sand soils, respectively, after being spilled onto the surface. The log K_{ow} values for this group of chemicals ranges from approximately 1.5 to 3.4, which further indicates they are weakly adsorbed by the soil (Table 14). Of the three wastes studied, the SRS had by far the greatest percentage of samples which contained a given waste constituent in both the soil core and soil-pore water samples. However, in general, a higher percentage of samples containing measurable quantities of constituents occurred in the soil-pore water samples (Table 14).

The statistical comparison of soil core and soil-pore water data from SRS treated soils (Appendix G) indicates that in general, there was no significant ($P = .05$) difference between the two sampling systems. Correlations for the paired data generally were less than 0.5 indicating a poor relationship. This was due to the large variability in the data in which standard deviations were typically two to four times the means. Thus, for these constituents, a large number of samples will be needed to get a representative value.

TABLE 14. THE PERCENTAGE OF SAMPLES FROM THREE SOILS HAVING A MEASURABLE QUANTITY OF EACH SRS CONSTITUENT THAT OCCURRED IN EITHER THE SOIL CORE SAMPLE ONLY, PORE WATER SAMPLE ONLY, OR BOTH

Chemical	Log K_{ow}	Soil Core	Pore Water	Both
		---------- (%) ----------		
Ethylbenzene	3.13	44	32	24
Xylene	3.17	26	67	7
2-butoxyethanol		39	26	35
1,2,4-trimethylbenzene		27	69	4
Acetophenone	1.58	15	72	13
2-phenyl-2-propanol		31	44	25
Isophorone	1.70	31	30	39
Naphthalene	3.35	12	88	0

Sample Availability

A frequent problem encountered when using porous ceramic cup samplers for obtaining a soil-pore water sample from the unsaturated zone is the lack of adequate sample volume for analytical purposes. In this study, a sample volume of 10 mL was considered the minimum needed for analysis. A total of 744 soil-pore water samples were attempted using the porous ceramic cup samplers. Of this number, 42.3% of the samples had a volume greater than or equal to 10 mL, 48.0% had a volume less than 10 mL but greater than zero, and 9.7% of the attempts produced no sample at all. Of this 9.7% when no sample could be obtained, 41.7% of the time it occurred both in the silt loam and clay soils, and 16.6% of the time in the sand soil. Soil-pore water samples are often more difficult to obtain from fine textured soils, since the porous ceramic cup extracts pore water mainly from fine pores which conduct liquids very slowly and hold the pore water very tightly. A comparison between the soils mositure content and the volume of pore water sample obtained indicates that the sand, loam, and clay soils used in this study must be, on the average, at or above a volumetric moisture content of about 13.8%, 32%, and 34.7%, respectively, to collect a 10 mL sample when using a continuous 55.4 kPa vacuum for 20 min. However, for the clay and loam soils, a large sample could sometimes be obtained at much lower moisture contents which may indicate that the porous ceramic cup has intercepted and is sampling a macropore. On the other hand, soil core samples could be obtained at all times, thus, theoretically allowing a 100 percent sampling efficiency.

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APPENDIX A

Cumulative volume (liters) of leachate passing the 25cm, 41 cm, 61 cm sampling depths and bottom of the barrel lysimeters as of the 2/7/85, 4/20/85, and 7/20/85 sampling dates.

TABLE A1. CUMMULATIVE VOLUME (LITERS) OF LEACHATE PASSING THE 25 CM, 41 CM, 61 CM SAMPLING DEPTHS AND BOTTOM OF THE BARREL LYSIMETERS AS OF THE 2/7/85 SAMPLING DATE

Soil	Treatment	Soil Depth 25 cm Liters	25 cm Pore Vol.	41 cm Liters	41 cm Pore Vol	61 cm Liters	61 cm Pore Vol	Bottom Liters	Bottom Pore Vol.
Norwood Silt Loam	API	72.6	0.75	53.2	0.55	24.1	0.25	8.0	0.08
		72.8	0.75	53.4	0.55	24.4	0.25	8.2	0.08
		81.2	0.84	61.8	0.64	32.7	0.34	16.6	0.17
	SRS	73.7	0.76	54.3	0.56	25.3	0.26	9.1	0.09
		72.6	0.75	53.2	0.55	24.1	0.25	8.0	0.08
		71.1	0.73	51.7	0.53	22.6	0.23	6.4	0.07
	WPW	76.9	0.79	57.5	0.59	28.4	0.29	12.2	0.13
		79.9	0.82	60.5	0.62	31.5	0.32	15.3	0.16
		78.5	0.81	59.1	0.61	30.1	0.31	13.9	0.14
	Control	72.6	0.75	53.2	0.55	24.2	0.25	8.0	0.08
		71.5	0.74	52.1	0.54	23.1	0.24	6.9	0.07
		78.2	0.81	58.8	0.61	29.7	0.31	13.6	0.14
Bastrop Clay	API	68.9	0.74	50.4	0.54	22.6	0.24	7.2	0.08
		67.8	0.73	49.3	0.53	21.5	0.23	6.1	0.06
		66.8	0.72	48.3	0.52	20.5	0.22	5.0	0.05
	SRS	66.3	0.72	47.7	0.52	19.9	0.22	4.5	0.05
		64.9	0.70	46.4	0.50	18.6	0.20	3.1	0.03
		66.8	0.72	48.2	0.52	20.4	0.22	5.0	0.05
	WPW	69.6	0.75	51.0	0.55	23.2	0.25	7.8	0.08
		69.3	0.75	50.8	0.55	23.0	0.25	7.6	0.08
		66.6	0.72	48.6	0.52	20.3	0.22	4.8	0.05
	Control	65.1	0.70	46.5	0.50	18.7	0.20	3.3	0.04
		68.4	0.74	49.9	0.54	22.1	0.24	6.7	0.07
		65.7	0.71	47.2	0.51	19.4	0.21	4.0	0.04

TABLE A1 CONTINUED.

Soil	Treatment*	Soil Depth 25 cm Liters	25 cm Pore Vol.	41 cm Liters	41 cm Pore Vol	61 cm Liters	61 cm Pore Vol	Bottom Liters	Bottom Pore Vol.
Padina Loam Sand	API	63.9	0.72	46.3	0.52	19.8	0.22	5.0	0.06
		78.6	0.89	60.9	0.69	34.4	0.39	19.7	0.22
		67.4	0.76	49.8	0.56	23.3	0.26	8.6	0.10
	SRS	70.5	0.80	52.9	0.60	26.4	0.30	11.6	0.13
		64.1	0.72	46.4	0.52	19.9	0.22	5.2	0.06
		64.9	0.73	47.2	0.53	20.7	0.23	6.0	0.07
	WPW	72.1	0.82	54.4	0.62	27.9	0.32	13.2	0.15
		67.0	0.76	49.4	0.56	22.9	0.26	8.2	0.09
		72.8	0.82	55.2	0.62	28.7	0.32	14.0	0.16
	Control	66.9	0.76	49.2	0.56	22.7	0.26	8.0	0.09
		67.5	0.76	49.9	0.56	23.4	0.26	8.6	0.10
		71.4	0.81	53.7	0.61	27.2	0.31	12.5	0.14

* API Separator Sludge (API), Solvent Recovery Sludge (SRS), Wood Preservative Waste (WPW).

TABLE A2. CUMMULATIVE VOLUME (LITERS) OF LEACHATE PASSING THE 25 CM, 41 CM, 61 CM SAMPLING DEPTHS AND BOTTOM OF THE BARREL LYSIMETERS AS OF THE 4/20/85 SAMPLING DATE

Soil	Treatment*	Soil Depth							
		25 cm		41 cm		61 cm		Bottom	
		Liters	Pore Vol.	Liters	Pore Vol	Liters	Pore Vol	Liters	Pore Vol.
Norwood Silt Loam	API	104.7	1.08	85.4	0.88	56.3	0.58	40.1	0.41
		107.2	1.10	87.8	0.90	58.7	0.60	42.6	0.44
		114.0	1.17	94.9	0.98	65.8	0.68	49.7	0.51
	SRS	104.8	1.08	85.4	0.88	56.4	0.58	40.2	0.41
		106.6	1.10	87.2	0.90	58.2	0.60	42.0	0.43
		106.3	1.10	86.9	0.89	57.8	0.60	41.6	0.43
	WPW	128.6	1.32	109.2	1.12	80.1	0.82	64.0	0.66
		122.7	1.26	103.3	1.06	74.2	0.76	58.1	0.60
		137.2	1.41	117.8	1.21	88.8	0.91	72.6	0.75
	Control	94.7	0.98	75.3	0.78	46.2	0.48	30.1	0.31
		102.9	1.06	83.5	0.86	54.5	0.56	38.3	0.39
		96.7	1.10	77.3	0.80	48.2	0.50	32.1	0.33
Bastrop Clay	API	75.8	0.82	57.3	0.62	29.5	0.32	14.0	0.15
		79.6	0.86	61.1	0.66	33.3	0.36	17.8	0.19
		75.4	0.81	56.9	0.61	29.1	0.31	13.7	0.15
	SRS	72.9	0.79	54.4	0.59	26.6	0.29	11.2	0.12
		74.0	0.80	55.5	0.60	27.7	0.30	12.2	0.13
		75.0	0.81	56.5	0.61	28.7	0.31	13.3	0.14
	WPW	74.4	0.80	55.9	0.60	28.1	0.30	12.6	0.14
		75.2	0.81	56.7	0.61	28.9	0.31	13.5	0.15
		75.9	0.82	57.3	0.61	29.5	0.32	14.1	0.15
	Control	66.0	0.71	47.4	0.51	19.7	0.21	4.2	0.05
		81.2	0.88	62.6	0.68	34.9	0.38	19.4	0.21
		66.2	0.71	47.6	0.51	19.8	0.21	4.4	0.05

TABLE A2 CONTINUED.

Soil	Treatment	Soil Depth 25 cm Liters	25 cm Pore Vol.	41 cm Liters	41 cm Pore Vol	61 cm Liters	61 cm Pore Vol	Bottom Liters	Bottom Pore Vol.
Padina Loam Sand	API	93.0	1.05	75.3	0.85	48.8	0.55	34.1	0.39
		113.5	1.28	95.9	1.08	69.4	0.78	54.6	0.62
		89.1	1.01	71.4	0.81	44.9	0.51	30.2	0.34
	SRS	137.7	1.56	120.1	1.36	93.6	1.06	78.8	0.89
		97.8	1.11	80.1	0.91	53.6	0.61	38.9	0.44
		107.5	1.22	89.8	1.02	63.3	0.72	48.6	0.55
	WPW	107.5	1.22	89.8	1.02	63.3	0.72	48.6	0.55
		118.6	1.34	101.0	1.14	74.5	0.84	59.7	0.68
		139.0	1.57	121.3	1.37	94.8	1.07	80.1	0.91
	Control	92.0	1.04	74.4	0.84	47.8	0.54	33.1	0.38
		83.6	0.94	65.9	0.75	39.4	0.45	24.7	0.28
		101.1	1.14	83.4	0.94	56.9	0.64	42.2	0.48

* API Separator Sludge (API), Solvent Recovery Sludge (SRS), Wood Preservative Waste (WPW).

TABLE A3. CUMMULATIVE VOLUME (LITERS) OF LEACHATE PASSING THE 25 CM, 41 CM, 61 CM SAMPLING DEPTHS AND BOTTOM OF THE BARREL LYSIMETERS AS OF THE 7/20/85 SAMPLING DATE

Soil	Treatment*	Soil Depth 25 cm Liters	25 cm Pore Vol.	41 cm Liters	41 cm Pore Vol	61 cm Liters	61 cm Pore Vol	Bottom Liters	Bottom Pore Vol.
Norwood Silt Loam	API	184.4	1.90	165.0	1.70	135.9	1.40	119.7	1.23
		177.7	1.83	158.0	1.63	128.9	1.33	112.8	1.16
		180.7	1.86	161.3	1.66	132.2	1.36	116.1	1.20
	SRS	154.8	1.60	135.4	1.39	106.3	1.10	90.2	0.93
		173.3	1.79	153.9	1.59	124.8	1.29	108.6	1.12
		166.9	1.72	147.5	1.52	118.4	1.22	102.2	1.05
	WPW	218.7	2.25	199.3	2.05	170.2	1.76	154.1	1.59
		215.0	2.22	195.6	2.02	166.6	1.72	150.4	1.55
		228.2	2.35	208.8	2.15	179.7	1.85	163.6	1.69
	Control	167.8	1.73	148.4	1.53	119.3	1.23	103.1	1.06
		161.5	1.66	142.1	1.46	113.0	1.16	96.9	1.00
		139.8	1.44	120.4	1.24	91.3	0.94	75.2	0.78
Bastrop Clay	API	88.7	0.96	70.2	0.76	42.4	0.46	27.0	0.29
		103.1	1.11	84.5	0.91	56.8	0.61	41.3	0.44
		84.0	0.91	65.5	0.71	37.7	0.41	22.2	0.24
	SRS	80.1	0.86	61.6	0.66	33.8	0.36	18.3	0.20
		80.3	0.87	61.8	0.67	34.0	0.37	18.6	0.20
		83.7	0.90	65.2	0.70	37.4	0.40	22.0	0.24
	WPW	79.6	0.86	61.1	0.66	32.3	0.36	17.8	0.19
		81.0	0.87	62.5	0.67	34.7	0.37	19.3	0.21
		84.7	0.91	66.2	0.71	38.4	0.41	23.0	0.25
	Control	66.0	0.71	47.4	0.51	19.7	0.21	4.2	0.04
		100.0	1.08	81.5	0.88	53.7	0.58	38.3	0.41
		67.5	0.73	49.0	0.53	21.2	0.23	5.7	0.06

TABLE A3 CONTINUED.

Soil	Treatment	Soil Depth 25 cm Liters	25 cm Pore Vol.	41 cm Liters	41 cm Pore Vol	61 cm Liters	61 cm Pore Vol	Bottom Liters	Bottom Pore Vol.
Padina Loam Sand	API	143.8	1.63	126.1	1.43	99.6	1.13	84.9	0.96
		159.0	1.80	141.3	1.60	114.8	1.30	100.1	1.13
		148.1	1.68	130.4	1.48	104.0	1.18	89.2	1.01
	SRS	214.2	2.42	196.5	2.22	170.0	1.92	155.3	1.76
		212.4	2.40	194.8	2.20	168.3	1.90	153.6	1.74
		172.4	1.95	154.7	1.75	128.2	1.45	113.5	1.28
	WPW	171.4	1.94	153.8	1.74	127.2	1.44	112.5	1.27
		205.4	2.32	187.7	2.12	161.2	1.82	146.5	1.66
		210.6	2.38	193.0	2.18	166.5	1.88	151.8	1.72
	Control	146.7	1.66	129.0	1.46	102.5	1.16	87.8	1.00
		128.7	1.46	111.1	1.26	84.6	0.96	69.8	0.79
		177.4	2.00	159.7	1.81	133.2	1.51	118.5	1.34

* API Separator Sludge (API), Solvent Recovery Sludge (SRS), Wood Preservative Waste (WPW).

APPENDIX B

Concentration of nineteen chemicals (Alkanes and PNA's) in soil-pore water ($\mu g\ L^{-1}$) and soil core ($\mu g\ kg^{-1}$) samples from undisturbed monoliths amended with API separator sludge.

ALKANES
LYSIMETER 3
WASTE API
SOIL LOAM

DEPTH (meters)	CHEMICAL	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25							
	NONANE	0	0	0	0	0	0
	DECANE	0	0	47.1	0	0	0
	UNDECANE	0	0	54.0	0	0	0
	DODECANE	0	0	0	0	0	0
	TRIDECANE	0	0	0	0	0	0
	TETRADECANE	0	0	0	0	0	0
	PENTADECANE	0	0	0	0	0	0
	HEPTADECANE	0	0	0	0	0	0
	NONADECANE	0	0	0	0	0	0
	TRICOSANE	0	0	0	0	0	0
	TETRACOSANE	0	0	0	0	0	0
0.41							
	NONANE	0	0	0	0	0	0
	DECANE	0	0	0	0	0	0
	UNDECANE	0	0	53.4	0	0	0
	DODECANE	0	0	0	0	0	0
	TRIDECANE	0	0	0	0	0	0
	TETRADECANE	0	0	0	0	0	0
	PENTADECANE	0	0	0	0	0	0
	HEPTADECANE	0	0	0	0	0	0
	NONADECANE	0	0	0	0	14.5	0
	TRICOSANE	0	0	0	0	0	0
	TETRACOSANE	0	0	0	0	0	0
0.61							
	NONANE	NA	0	0	0	0	0
	DECANE		0	0	0	0	0
	UNDECANE		0	0	0	0	0
	DODECANE		0	0	0	0	0
	TRIDECANE		0	0	0	0	0
	TETRADECANE		0	0	0	0	0
	PENTADECANE		0	0	0	0	0
	HEPTADECANE		0	0	0	0	0
	NONADECANE		0	0	0	0	0
	TRICOSANE		0	0	0	0	0
	TETRACOSANE		0	0	0	0	0

ALKANES
LYSIMETER 4
WASTE API
SOIL LOAM

DEPTH (meters)	CHEMICAL	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25							
	NONANE	0	0	0	NS	0	0
	DECANE	0	0	0		0	0
	UNDECANE	6.4	0	0		0	0
	DODECANE	0	0	0		0	0
	TRIDECANE	0	0	0		0	0
	TETRADECANE	0	0	0		0.1	0
	PENTADECANE	0	0	0		0.3	0
	HEPTADECANE	0	0	0.2		4.4	0
	NONADECANE	0	0	0		1.0	0
	TRICOSANE	0	0	1.1		7.6	0
	TETRACOSANE	0	0	0		0	0
0.41							
	NONANE	0	0	NA	0	0	0
	DECANE	0	0		0	0	0
	UNDECANE	0	0		0	0	0
	DODECANE	0	0		0	0	0
	TRIDECANE	0	0		0	0	0
	TETRADECANE	0	0		0	0	0
	PENTADECANE	0	0		0	0	0
	HEPTADECANE	0	0		0	0	0
	NONADECANE	0	0		0	4.1	0
	TRICOSANE	0	0		0	1.9	0
	TETRACOSANE	0	0		0	0	0
0.61							
	NONANE	NA	NS	0	0	NA	NS
	DECANE			0	0		
	UNDECANE			31.4	0		
	DODECANE			0	0		
	TRIDECANE			0	0		
	TETRADECANE			0	0		
	PENTADECANE			0	0		
	HEPTADECANE			0	0		
	NONADECANE			0	0		
	TRICOSANE			0	0		
	TETRACOSANE			0	0		

ALKANES
LYSIMETER 6
WASTE API
SOIL LOAM

DEPTH (meters)	CHEMICAL	FEB 7 CORE	PORE	APRIL 20 CORE	PORE	JULY 20 CORE	PORE
0.25							
	NONANE	0	NS	24.6	0	0	0
	DECANE	0		0	0	0	0
	UNDECANE	15.6		21.7	0	0	0
	DODECANE	0		0.7	0	0	0
	TRIDECANE	0		0	0	0	0
	TETRADECANE	0		0	0	0.8	0
	PENTADECANE	0		0	0	1.0	0
	HEPTADECANE	0		0	0	18.8	0
	NONADECANE	0		4.1	0	6.0	0
	TRICOSANE	0		4.9	0	0	0
	TETRACOSANE	0		0	0	0	0
0.41							
	NONANE	0	NS	NA	NS	NA	0
	DECANE	0					0
	UNDECANE	0					0
	DODECANE	0					0
	TRIDECANE	0					0
	TETRADECANE	0					0
	PENTADECANE	0					0
	HEPTADECANE	0					0
	NONADECANE	0					0
	TRICOSANE	0					0
	TETRACOSANE	0					0
0.61							
	NONANE	NA	0	0	0	0	0
	DECANE		0	0	0	0	0
	UNDECANE		0	0	0	0.7	0
	DODECANE		0	0	0	0	0
	TRIDECANE		0	0	0	0	0
	TETRADECANE		0	0	0	0	0
	PENTADECANE		0	0	0	1.4	0
	HEPTADECANE		0	0	0	0	0
	NONADECANE		0	0	0	4.1	0
	TRICOSANE		0	0	0	0	0
	TETRACOSANE		0	0	0	0	0

ALKANES
LYSIMETER 16
WASTE API
SOIL CLAY

DEPTH (meters)	CHEMICAL	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25	NONANE	NA	NS	0	0	0	11.7
	DECANE			0	0	0	15.1
	UNDECANE			0	0	0	16.0
	DODECANE			0	0	0	3.4
	TRIDECANE			0	0	0	23.8
	TETRADECANE			0	0	0	0
	PENTADECANE			0	0	0	0
	HEPTADECANE			3.2	0	11.1	0
	NONADECANE			0	0	15.0	0
	TRICOSANE			0	0	0	0
	TETRACOSANE			29.4	0	0	0
0.41	NONANE	0	NS	0	0	0	0
	DECANE	0		0	0	0	25.7
	UNDECANE	0		0	0	0	16.8
	DODECANE	0		0	0	0	3.8
	TRIDECANE	0		0	0	0	0
	TETRADECANE	0		0	0	0	0
	PENTADECANE	0		0	0	0	0
	HEPTADECANE	0		0	0	0	0
	NONADECANE	0		0	0	56.4	0
	TRICOSANE	0		0	0	0	0
	TETRACOSANE	0		0	0	0	0
0.61	NONANE	NA	NS	NA	0	0	9.1
	DECANE				0	0	14.4
	UNDECANE				0	0	14.9
	DODECANE				0	0	3.4
	TRIDECANE				0	0	25.2
	TETRADECANE				0	0	5.7
	PENTADECANE				0	0	3.3
	HEPTADECANE				0	9.4	0
	NONADECANE				0	11.0	0
	TRICOSANE				0	0	0
	TETRACOSANE				0	0	0

ALKANES
LYSIMETER #18
WASTE API
SOIL CLAY

DEPTH (meters)	CHEMICAL	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25							
	NONANE	0	NS	0	0	0	NS
	DECANE	0		0	0	0	
	UNDECANE	3.2		0	0	0	
	DODECANE	0		0	0	6.8	
	TRIDECANE	0		0	0	0	
	TETRADECANE	0		0	0	0	
	PENTADECANE	0.8		0	0	0	
	HEPTADECANE	0		0	0	0	
	NONADECANE	0		1.6	0	2.4	
	TRICOSANE	3.6		0	0	0	
	TETRACOSANE	0		7.6	0	0	
0.41							
	NONANE	0	NS	NA	0	0	0
	DECANE	0			0	0	12.0
	UNDECANE	0			0	0	15.1
	DODECANE	3.2			0	0	10.7
	TRIDECANE	13.6			0	0.1	9.8
	TETRADECANE	8.4			0	0	4.9
	PENTADECANE	25.2			0	0.3	4.9
	HEPTADECANE	1675.2			0	15.2	0
	NONADECANE	182.8			0	108.0	0
	TRICOSANE	61.2			0	3.2	0
	TETRACOSANE	116.0			0	0	0
0.61							
	NONANE	0	0	0	0	0	0
	DECANE	0	0	0	0	0	0
	UNDECANE	0	0	0	0	1.2	0
	DODECANE	0	0	0	0	0	0
	TRIDECANE	0	0	0	0	0	0
	TETRADECANE	31.2	0	0	0	0	0
	PENTADECANE	34.8	0	0	0	2.0	0
	HEPTADECANE	287.0	1.2	3.6	0	1.2	0
	NONADECANE	204.0	4.0	0	0	4.4	0
	TRICOSANE	0	0	0	0	0	0
	TETRACOSANE	0	21.6	24.8	0	7.2	0

ALKANES
LYSIMETER #20
WASTE API
SOIL CLAY

DEPTH (meters)	CHEMICAL	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25							
	NONANE	0	NS	0	NS	0	0
	DECANE	0		0		0	0
	UNDECANE	0		0		0	0
	DODECANE	0		0		0.7	0
	TRIDECANE	0		0		0	0
	TETRADECANE	0		0		0	0
	PENTADECANE	0		0		2.8	0
	HEPTADECANE	0		0		1.1	0
	NONADECANE	0		0		2.5	0
	TRICOSANE	0		0		394.3	0
	TETRACOSANE	0		0		0	0
0.41							
	NONANE	0	0	0	0	NA	63.5
	DECANE	0	0	0	0		96.0
	UNDECANE	0	0	9.6	0		97.4
	DODECANE	0	0	0	0		56.1
	TRIDECANE	0	0	0.4	0		43.5
	TETRADECANE	0	0	0	0		17.4
	PENTADECANE	0	0	0.7	0		3.3
	HEPTADECANE	0	0	4.6	0		0
	NONADECANE	0	0	71.3	0		4.7
	TRICOSANE	0	0	0	0		0
	TETRACOSANE	0	0	0	0		0
0.61							
	NONANE	NA	0	0	0	0	0
	DECANE		0	0	0	0	0
	UNDECANE		0	0	0	0	0
	DODECANE		0	0	0	0	0
	TRIDECANE		0	0	0	0	0
	TETRADECANE		0	0	0	0	0
	PENTADECANE		0	0	0	8.1	0
	HEPTADECANE		0	2.8	0	14.7	0
	NONADECANE		0	1.4	0	58.5	0
	TRICOSANE		0	0	0	28.8	0
	TETRACOSANE		0	0	0	0	0

ALKANES
LYSIMETER 28
WASTE API
SOIL SAND

DEPTH (meters)	CHEMICAL	FEB 7 CORE	PORE	APRIL 20 CORE	PORE	JULY 20 CORE	PORE
0.25							
	NONANE	0	0	0	0	0	NS
	DECANE	0	0	0	0	0	
	UNDECANE	41.6	14.8	0	0	0	
	DODECANE	4.4	3.2	0	0	0	
	TRIDECANE	48.4	2.8	0	0	0	
	TETRADECANE	132.8	0	0	0	0	
	PENTADECANE	47.2	0	1.6	0	4.0	
	HEPTADECANE	0	0	2.8	0	0.8	
	NONADECANE	0	0	3.6	0	1.6	
	TRICOSANE	17.6	0	0	0	0	
	TETRACOSANE	0	0	0	0	0	
0.41							
	NONANE	0	0	0	0	0	0
	DECANE	0	0	0	0	0	32.8
	UNDECANE	0	0	0	0	0	34.8
	DODECANE	99.6	0	0	0	0	18.0
	TRIDECANE	0	0	0	0	0	0
	TETRADECANE	0	0	0.2	0	9.2	0
	PENTADECANE	0	0	1.2	0	0	0
	HEPTADECANE	0	0	16.0	0	0	0
	NONADECANE	0	0	0	0	0	0
	TRICOSANE	0	0	0	0	0	0
	TETRACOSANE	0	0	0	0	0	0
0.61							
	NONANE	NA	NS	NS	0	0	NS
	DECANE				0	0	
	UNDECANE				0	0	
	DODECANE				0	0	
	TRIDECANE				0	0	
	TETRADECANE				0	0	
	PENTADECANE				0	3.6	
	HEPTADECANE				0	0	
	NONADECANE				0	0	
	TRICOSANE				0	0	
	TETRACOSANE				0	0	

ALKANES
LYSIMETER 33
WASTE API
SOIL SAND

DEPTH (meters)	CHEMICAL	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25							
	NONANE	0	0	0	0	NA*	NS
	DECANE	0	0	0	0		
	UNDECANE	0	0	0	0		
	DODECANE	0	0	0	0		
	TRIDECANE	14.0	0	0	0		
	TETRADECANE	24.0	0	0.1	0		
	PENTADECANE	20.8	0	0	0		
	HEPTADECANE	0	0	0.6	0		
	NONADECANE	3.2	0	0	0		
	TRICOSANE	0	0	0	0		
	TETRACOSANE	4.8	0	1.0	0		
0.41							
	NONANE	0	0	0	0	0	0
	DECANE	0	0	0	0	0	0
	UNDECANE	0	0	0	0	0	0
	DODECANE	0	0	0	0	0	0
	TRIDECANE	0	0	0	0	0	0
	TETRADECANE	0	0	0	0	0	0
	PENTADECANE	0	0	4.0	0	0	0
	HEPTADECANE	0	0	0	0	6.8	0
	NONADECANE	0	0	15.6	0	1.6	0
	TRICOSANE	0	0	0	0	0	0
	TETRACOSANE	0	0	32.8	0	0	0
0.61							
	NONANE	NA	0	NA	0	0	0
	DECANE		0		0	0	0
	UNDECANE		0		0	0	0
	DODECANE		0		0	0	0
	TRIDECANE		0		0	0	0
	TETRADECANE		0		0	0	0
	PENTADECANE		0		0	0	0
	HEPTADECANE		0		0	6.8	0
	NONADECANE		0		0	5.6	0
	TRICOSANE		0		0	0	0
	TETRACOSANE		0		0	13.6	0

* SAMPLE DESTROYED

ALKANES
LYSIMETER 35
WASTE API
SOIL SAND

DEPTH (meters)	CHEMICAL	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25							
	NONANE	0	0	0	0	0	0
	DECANE	0	0	0	0	0	0
	UNDECANE	0	0	2.1	0	0	0
	DODECANE	0	0	0	0	0	0
	TRIDECANE	7.3	0	0.9	0	0	0
	TETRADECANE	5.0	0	0	0	2.6	0
	PENTADECANE	0	0	0	0	2.6	0
	HEPTADECANE	0	0	0	0	0	0
	NONADECANE	0	0	2.8	0	0	0
	TRICOSANE	0	0	0	0	31.6	0
	TETRACOSANE	0	0	0	0	75.6	0
0.41							
	NONANE	0	NS	0	NS	0	80.5
	DECANE	0		0		0	88.6
	UNDECANE	0		0		0	110.3
	DODECANE	0		0		0	53.3
	TRIDECANE	48.3		0		1.2	51.6
	TETRADECANE	0		0		2.8	16.3
	PENTADECANE	0		0		0	0
	HEPTADECANE	0		0		1.4	0
	NONADECANE	0		11.7		0.6	0
	TRICOSANE	0		0		3.9	0
	TETRACOSANE	0		0		0	0
0.61							
	NONANE	NA	0	0	0	0	32.0
	DECANE		0	0	0	0	33.7
	UNDECANE		0	0	0	0	37.5
	DODECANE		0	0	0	0	22.9
	TRIDECANE		0	3.1	0	0	13.8
	TETRADECANE		0	0	0	0	0
	PENTADECANE		0	4.0	0	3.4	0
	HEPTADECANE		0	15.2	0	0	0
	NONADECANE		0	4.5	0	4.4	0
	TRICOSANE		0	0	0	0	0
	TETRACOSANE		0	0	0	0	0

PNA'S
LYSIMETER 3
WASTE API
SOIL LOAM

DEPTH (meters)	CHEMICAL	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25							
	ACENAPHTHYLENE	0	0	17.1	0	5.8	0
	ACENAPHTHENE	0	0	0	0	4.8	0
	FLUORENE	0	0	12.5	0	11.9	0
	PHENANTHRENE	0	0	0	0	0	0
	ANTHRACENE	0	0	0	0	0	0
	FLUORANTHENE	0	0	0	0	0	0
	PYRENE	0	0	8.9	0	0	0
	CHRYSENE	0	0	3.5	0	0	0
16"							
	ACENAPHTHYLENE	0	0	0	0	7.8	0
	ACENAPHTHENE	0	0	0	0	2.1	0
	FLUORENE	0	0	2.9	0	7.2	0
	PHENANTHRENE	0	0	0	0	1.9	0
	ANTHRACENE	0	0	0	0	0.5	0
	FLUORANTHENE	0	0	0	0	1.0	0
	PYRENE	0	0	0.6	0	1.0	0
	CHRYSENE	0	0	0	0	0	0
24"							
	ACENAPHTHYLENE	NA	0	0	0	2.0	0
	ACENAPHTHENE		0	0	0	1.9	0
	FLUORENE		0	0.6	0	6.0	0
	PHENANTHRENE		0	0	0	2.0	0
	ANTHRACENE		0	0	0	0.6	0
	FLUORANTHENE		0	0	0	0.6	0
	PYRENE		0	0	0	0.6	0
	CHRYSENE		0	0	0	0	0

PNA'S
LYSIMETER 4
WASTE API
SOIL LOAM

DEPTH (meters)	CHEMICAL	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25							
	ACENAPHTHYLENE	0	0	0	NS	0	0
	ACENAPHTHENE	0	0	4.4		1.3	0
	FLUORENE	0	0	0.3		0.6	0
	PHENANTHRENE	0	0	0.5		2.6	0
	ANTHRACENE	0	0	0.1		0.9	0
	FLUORANTHENE	0	0	0.4		1.1	0
	PYRENE	0	0	2.8		0.6	0
	CHRYSENE	0	0	0.1		0	0
0.41							
	ACENAPHTHYLENE	0	0	NA	0	0	0
	ACENAPHTHENE	0	0		0	3.6	0
	FLUORENE	0	0		0	0.4	0
	PHENANTHRENE	0	0		0	4.0	0
	ANTHRACENE	0	0		0	1.5	0
	FLUORANTHENE	0	0		0	2.3	0
	PYRENE	0	0		0	0.8	0
	CHRYSENE	0	0		0	0	0
0.61							
	ACENAPHTHYLENE	NA	NS	0	0	NA	NS
	ACENAPHTHENE			0	0		
	FLUORENE			6.3	0		
	PHENANTHRENE			0	0		
	ANTHRACENE			0	0		
	FLUORANTHENE			0	0		
	PYRENE			1.9	0		
	CHRYSENE			0	0		

PNA'S
LYSIMETER 6
WASTE API
SOIL SILT

DEPTH (meters)	CHEMICAL	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25	ACENAPHTHYLENE	0	NS	0	0	7.9	0
	ACENAPHTHENE	0		0	0	3.6	0
	FLUORENE	0		1.2	0	2.0	0
	PHENANTHRENE	0		0	0	5.7	0
	ANTHRACENE	0		0	0	2.0	0
	FLUORANTHENE	0		12.7	0	2.1	0
	PYRENE	0		1.2	0	1.5	0
	CHRYSENE	0		0.4	0	3.6	0
0.41	ACENAPHTHYLENE	3.6	NS	NA	NS	NA	0
	ACENAPHTHENE	0					0
	FLUORENE	0					0
	PHENANTHRENE	0					0
	ANTHRACENE	0					0
	FLUORANTHENE	0.2					0
	PYRENE	0					0
	CHRYSENE	0					0
0.61	ACENAPHTHYLENE	NA	0	0	0	0	0
	ACENAPHTHENE		0	0	0	1.5	0
	FLUORENE		0	5.0	0	3.2	0
	PHENANTHRENE		0	0	0	4.2	0
	ANTHRACENE		0	0	0	1.5	0
	FLUORANTHENE		0	0	0	2.4	0
	PYRENE		0	0	0	1.9	0
	CHRYSENE		0	0	0	1.8	0

PNA'S
LYSIMETER 16
WASTE API
SOIL CLAY

DEPTH (meters)	CHEMICAL	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25							
	ACENAPHTHYLENE	NA	NS	0	0	0	0
	ACENAPHTHENE			0	0	5.8	0
	FLUORENE			2.2	0	26.8	0
	PHENANTHRENE			0	0	1.0	0
	ANTHRACENE			0	0	1.1	0
	FLUORANTHENE			0	0	0	0
	PYRENE			3.0	0	6.0	0
	CHRYSENE			0	0	0	0
0.41							
	ACENAPHTHYLENE	0	NS	0	0	0	0
	ACENAPHTHENE	0		0	0	5.0	0
	FLUORENE	0		0.6	0	60.6	0
	PHENANTHRENE	0		0	0	3.7	0
	ANTHRACENE	0		0	0	2.3	0
	FLUORANTHENE	0		0	0	0	0
	PYRENE	0		0	0	20.4	0
	CHRYSENE	0		0	0	0	0
0.61							
	ACENAPHTHYLENE	NA	NS	NA	0	0	0
	ACENAPHTHENE				0	14.3	0
	FLUORENE				0	32.0	0
	PHENANTHRENE				0	1.3	0
	ANTHRACENE				0	0.6	0
	FLUORANTHENE				0	1.9	0
	PYRENE				0	4.4	0
	CHRYSENE				0	0	0

PNA'S
LYSIMETER #18
WASTE API
SOIL CLAY

DEPTH (meters)	CHEMICAL	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25							
	ACENAPHTHYLENE	1.2	0	0	0	8.8	NS
	ACENAPHTHENE	2.0	0	0	0	6.8	
	FLUORENE	26.8	0	0.4	0	2.8	
	PHENANTHRENE	0	2.0	0	0	0	
	ANTHRACENE	0	0	0	0	0	
	FLUORANTHENE	0	0	0	0	0	
	PYRENE	7.2	0	0.1	0	0.2	
	CHRYSENE	0	0	2.0	0	0	
0.41							
	ACENAPHTHYLENE	0	NS	0	0	0	0
	ACENAPHTHENE	20.8		0	0	0.8	0
	FLUORENE	675.2		1.6	0	38.4	0
	PHENANTHRENE	0		0	0	0	0
	ANTHRACENE	0		0	0	2.8	0
	FLUORANTHENE	27.6		0.3	0	0.8	0
	PYRENE	38.8		0.1	0	60.8	0
	CHRYSENE	0		0	0	1.2	0
0.61							
	ACENAPHTHYLENE	0	NS	24.4	0	0	0
	ACENAPHTHENE	0		14.0	0	1.2	0
	FLUORENE	638.8		6.4	0	2.8	0
	PHENANTHRENE	0		1.2	0	0	0
	ANTHRACENE	0		0	0	0.1	0
	FLUORANTHENE	0		0	0	0.2	0
	PYRENE	108.4		6.8	0	0.2	0
	CHRYSENE	0		0	0	0	0

PNA'S
LYSIMETER #20
WASTE API
SOIL CLAY

DEPTH (meters)	CHEMICAL	FEB 20 CORE	FEB 20 PORE	APRIL 7 CORE	APRIL 7 PORE	JULY 20 CORE	JULY 20 PORE
0.25							
	ACENAPHTHYLENE	0	NS	0	NS	18.7	0
	ACENAPHTHENE	0		1.2		9.8	0
	FLUORENE	1.5		10.9		30.9	0
	PHENANTHRENE	0		0		0	0
	ANTHRACENE	0		0		0	0
	FLUORANTHENE	0		0		2.0	0
	PYRENE	1.3		0		3.7	0
	CHRYSENE	0		0		0	0
0.41							
	ACENAPHTHYLENE	0	0	7.6	0	NA	0
	ACENAPHTHENE	0	0	9.6	0		0.3
	FLUORENE	0	0	28.8	0		0
	PHENANTHRENE	0	0	0	0		0
	ANTHRACENE	0	0	0	0		0
	FLUORANTHENE	0	0	0.3	0		0
	PYRENE	0	0	0.8	0		2.0
	CHRYSENE	0	0	0	0		0
0.61							
	ACENAPHTHYLENE	NA	0	0.7	0	1.6	0
	ACENAPHTHENE		0	6.6	0	5.3	0
	FLUORENE		0	12.3	0	60.6	208.7
	PHENANTHRENE		0	0	0	0	8.9
	ANTHRACENE		0	0	0	0	0
	FLUORANTHENE		0	0.2	0	4.5	5.3
	PYRENE		0	0.6	0	0	43.6
	CHRYSENE		0	0	0	0	0

PNA'S
LYSIMETER 28
WASTE API
SOIL SAND

DEPTH (meters)	CHEMICAL	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25							
	ACENAPHTHYLENE	82.4	0	10.4	0	4.4	NS
	ACENAPHTHENE	21.2	0	5.6	0	5.2	
	FLUORENE	26.4	0	179.6	0	6.8	
	PHENANTHRENE	0.4	0	0	0	0	
	ANTHRACENE	0.8	0	0	0	0	
	FLUORANTHENE	0.3	0	0	0	0	
	PYRENE	2.7	0	0	0	0	
	CHRYSENE	0	0	0	0	0	
0.41							
	ACENAPHTHYLENE	0	0	12.4	0	0	0
	ACENAPHTHENE	60.4	0	5.6	0	1.6	0
	FLUORENE	4.4	0	89.2	0	2.4	0
	PHENANTHRENE	0	0	0	0	0	0
	ANTHRACENE	0	0	0	0	0.4	0
	FLUORANTHENE	4.4	0	11.2	0	0.2	0
	PYRENE	4.8	0	6.8	0	0	0
	CHRYSENE	0	0	0	0	0	0
0.61							
	ACENAPHTHYLENE	NA	NS	NS	0	1.8	NS
	ACENAPHTHENE				0	9.1	
	FLUORENE				0	27.9	
	PHENANTHRENE				0	0	
	ANTHRACENE				0	0	
	FLUORANTHENE				0	0	
	PYRENE				0	0	
	CHRYSENE				0	0	

PNA'S
LYSIMETER 33
WASTE API
SOIL SAND

DEPTH (meters)	CHEMICAL	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25							
	ACENAPHTHYLENE	32.8	0	2.8	0	NA+	NS
	ACENAPHTHENE	10.0	0	1.6	0		
	FLUORENE	21.6	0	2.0	0		
	PHENANTHRENE	0	0	0.4	0		
	ANTHRACENE	0	0	0	0		
	FLUORANTHENE	0	0	0.8	0		
	PYRENE	6.0	0	0.4	0		
	CHRYSENE	0	0	0	0		
0.41							
	ACENAPHTHYLENE	0	0	36.0	0	2.4	0
	ACENAPHTHENE	0	0	8.4	0	30.8	0
	FLUORENE	2.0	0	7.6	0	28.8	0
	PHENANTHRENE	0	0	2.0	0	1.2	0
	ANTHRACENE	2.4	0	0	0	0	0
	FLUORANTHENE	0	0	5.2	0	2.8	0
	PYRENE	0	0	0	0	1.6	0
	CHRYSENE	0	0	0	0	0	0
0.61							
	ACENAPHTHYLENE	NA	0	NS	0	4.0	0
	ACENAPHTHENE		0		0	6.0	0
	FLUORENE		0		0	21.6	0
	PHENANTHRENE		0		0	0.8	0
	ANTHRACENE		0		0	0	0
	FLUORANTHENE		0		0	1.2	0
	PYRENE		0		0	0.4	0
	CHRYSENE		0		0	0	0

PNA'S
LYSIMETER 35
WASTE API
SOIL SAND

DEPTH (meters)	CHEMICAL	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25							
	ACENAPHTHYLENE	0	0	21.2	0	86.0	0
	ACENAPHTHENE	8.8	0	0.8	0	25.0	0
	FLUORENE	2.0	0	7.6	0	157.1	0
	PHENANTHRENE	0	0	0	0	0	0
	ANTHRACENE	0	0	0	0	0	0
	FLUORANTHENE	0	0	0.4	0	3.1	0
	PYRENE	0	0	0	0	3.3	0
	CHRYSENE	0	0	0	0	0	0
0.41							
	ACENAPHTHYLENE	0	NS	32.1	NS	110.3	0
	ACENAPHTHENE	0		8.1		38.9	10.0
	FLUORENE	0.5		30.1		27.3	0
	PHENANTHRENE	0		0		0.2	0
	ANTHRACENE	0.6		0		0.2	0
	FLUORANTHENE	0		1.1		0.8	0
	PYRENE	0		0		0.2	0
	CHRYSENE	0		0		0	0
0.61							
	ACENAPHTHYLENE	NA	0	25.4	0	0	0
	ACENAPHTHENE		0	0	0	2.1	0
	FLUORENE		0	19.8	0	13.1	0
	PHENANTHRENE		0	0	0	0	0
	ANTHRACENE		0	0	0	0	0
	FLUORANTHENE		0	1.4	0	0.3	0
	PYRENE		0	0	0	1.2	0
	CHRYSENE		0	0	0	0	0

APPENDIX C

Statistical comparison of the alkane and PNA concentrations measured in soil core and soil-pore water samples in three soils treated with API separator sludge

TABLE C1. API WASTE-ALKANES

			Nonane Mean ± SD(n)	Decane Mean ± SD (n)	Undecane Mean ± SD (n)	Dodecane Mean ± SD (n)	Tridecane Mean ± SD (n)	Tetradecane Mean ± SD (n)
Sand	Core	ID †		0.0a*± 0.0(3)	8.8a ± 18.6(5)	20.8a ± 44.3(5)	10.6a ± 17.2(7)	29.5a ± 51.3(6)
	Pore	ID		52.0a ± 32.0(3)	39.6a ± 42.3(5)	19.4a ± 21.1(5)	9.9a ± 19.3(7)	2.7a ± 6.5(6)
	Regression	ID		NA ††	P_2= -0.81C + 46.7 r^2 = 0.13 df = 4	P_2= -0.25C + 24.7 r^2 = 0.29 df = 4	P_2= -0.30C + 13.0 r^2 = 0.07 df = 6	P_2= -0.03C + 3.61 r^2 = 0.06 df = 5
Loam	Core	ID		ID	27.8b ± 22.6(6)	ID	ID	ID
	Pore	ID		ID	0.0a ± 0.0(6)	ID	ID	ID
	Regression	ID		ID	NA	ID	ID	ID
Clay	Core	ID		0.0a ± 0.0(4)	1.8a ± 4.0(6)	0.2a ± 0.45(5)	0.0a ± 0.0(3)	10.3a ± 17.9(3)
	Pore	ID		16.8b ± 6.3(4)	10.5a ± 8.2(6)	4.2a ± 4.1 (5)	19.7a ± 8.4(3)	3.7a ± 3.2(3)
	Regression	ID		NA	P_2= -1.4C + 13.1 r^2 = 0.49 df = 5	P_2= -5.25C + 5.25 r^2 = 0.33 df = 4	NA	P_2= -0.18C + 5.5 r^2 = 0.98 df = 2

† ID = insufficient paired data to do statistical analysis.

†† NA = regression analysis cannot be applied to this data set.

* = means within a given soil and chemical combination followed by the same letter do not differ significantly at p = 0.05.

TABLE C1. API WASTE-ALKANES

		Pentadecane Mean ± SD (n)	Heptadecane Mean ± SD (n)	Nonadecane Mean ± SD (n)	Tricosane Mean ± SD (n)	Tetracosane Mean ± SD (n)
Sand	Core	10.6a* ± 16.0(8)	7.1b ± 6.2(7)	4.9b ± 4.4(9)	18.0a ± 14.0(3)	25.8a ± 30.7(5)
	Pore	0.0a ± 0.0(8)	0.0a ± 0.0(7)	0.0a ± 0.0(9)	0.0a ± 0.0(3)	0.0a ± 0.0(5)
	Regression	NA††	NA	NA	NA	NA
Loam	Core	ID†	ID	5.7b ± 4.8(6)	5.0a ± 3.0(3)	ID
	Pore	ID	ID	0.0a ± 0.0(6)	0.0a ± 0.0(3)	ID
	Regression	ID	ID	NA	NA	ID
Clay	Core	7.0a ± 12.6(7)	32.2a ± 84.7(11)	48.5b ± 62.8 (11)	142.0a ± 218.0(3)	13.8a ± 12.5(5)
	Pore	1.1a ± 2.0(7)	0.1a ± 0.3(11)	0.4a ± 1.2 (11)	0.0a ± 0.0 (3)	4.4a ± 9.8(5)
	Regression	$P_2 = -0.06C + 1.55$ $r^2 = 0.13$ df = 6	$P_2 = 0.004C - 0.02$ $r^2 = 0.99$ df = 10	$P_2 = 0.02C - 0.40$ $r^2 = 0.67$ df = 10	NA	$P_2 = 0.36C + 6.35$ $r^2 = 0.38$ df = 4

† ID = insufficient paired data to do statistical analysis.

†† NA = regression analysis cannot be applied to this data set.

* = means within a given soil and chemical combination followed by the same letter do not differ significantly at p = 0.05.

TABLE C2. API WASTE PNA's

	Acenaphthylene Mean ± SD (n)	Acenaphthene Mean ± SD (n)	Fluorene Mean ± SD (n)	Phenanthrene Mean ± SD (n)
Sand Core	35.3b* ± 36.9(12)	15.2b ± 17.0(15)	36.1b ± 54.1(17)	1.3a ± 0.6(3)
Pore	0.0a ± 0.0(12)	0.7a ± 2.6(15)	0.0a ± 0.0(17)	0.0a ± 0.0(3)
Regression	NA††	P_2= 0.06C - 0.23 r^2 =0.15 df = 14	NA	NA
Loam Core	8.2b ± 5.5(5)	2.9b ± 1.5(7)	5.0b ± 4.0(12)	3.5b ± 1.5(6)
Pore	0.0a ± 0.0(5)	0.0a ± 0.0(7)	0.0a ± 0.0(12)	0.0a ± 0.0(6)
Regression	NA	NA	NA	NA
Clay Core	9.2a ± 10.0(6)	6.8b ± 4.7(11)	23.7a ± 20.6(14)	1.2a ± 1.5(6)
Pore	0.0a ± 0.0(6)	0.0a ± 0.0(11)	14.9a ± 55.9(14)	1.8a ± 3.6(6)
Regression	NA	NA	P_2= 1.42C - 18.7 r^2 = 0.27 df = 13	P_2= -1.2C + 3.2 R^2 = 0.23 df = 5

†† NA = regression analysis cannot be applied to this data set.

* = means within a given soil and chemical combination followed by the same letter do not differ significantly at p = 0.05.

TABLE C2. API WASTE PNA's

		Anthracene Mean ± SD (n)	Fluoranthene Mean ± SD (n)	Pyrene Mean ± SD (n)	Chrysene Mean ± SD (n)
Sand	Core	ID†	3.3b*± 3.2(9)	3.9b ± 2.2(7)	ID
	Pore	ID	0.0a ± 0.0(9)	0.0a ± 0.0(7)	ID
	Regression	ID	NA	NA	ID
Loam	Core	1.5b ± 0.5(6)	3.1a ± 4.4(7)	2.3a ± 2.8(8)	3.3b ± 1.2(3)
	Pore	0.0a ± 0.0(6)	0.0a ± 0.0(7)	0.8a ± 2.1(8)	0.0a ± 0.0(3)
	Regression	NA ††	NA	$P = -0.24C + 1.3$ $r^2 = 0.10$ df = 7	NA
Clay	Core	1.8b ± 1.0(4)	2.5a ± 1.7(4)	10.4a ± 17.7(11)	ID
	Pore	0.0a ± 0.0(4)	1.3a ± 2.5(4)	4.0a ± 13.3(11)	ID
	Regression	NA	$P_2 = 1.39C - 2.22$ $r^2 = 0.93$ df = 3	$P_2 = -0.15C + 5.52$ $r^2 = 0.04$ df = 10	ID

† ID = insufficient paired data to do statistical analysis.

†† NA = regression analysis cannot be applied to this data set.

* = means within a given soil and chemical combination followed by the same letter do not differ significantly at p = 0.05.

APPENDIX D

Concentration of eleven chemicals in soil-pore water ($\mu g\ L^{-1}$) and soil core ($\mu g\ kg^{-1}$) samples from undisturbed monoliths amended with wood preservative waste

LYSIMETER # 2
WASTE WPW
SOIL SILT

DEPTH (meters)	CHEMICAL	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25							
	PHENOL	5.8 *	NS	0	0	0	0
	2 CHLOROPHENOL	0		0	0	0	0
	2 NITROPHENOL	5.2 *		0	0	0	0
	2,4 DIMETHYLPHENOL	0		0	0	0	0
	2,4 DICHLOROPHENOL	3.0 *		0	0	0	0
	P-CHLORO-M-CRESOL	0		0	0	0	0
	2,4,6 TRICHLOROPHENOL	0		0	0	0	0
	2,4 DINITROPHENOL	0		0	0	0	0
	4 NITROPHENOL	0		0	0	0	0
	4,6 DINITRO-O-CRESOL	0		1.0 *	0	0	0
	PENTACHLOROPHENOL	0		0	0	0	0
0.41							
	PHENOL	0	0	0	0	0	0
	2 CHLOROPHENOL	0	0	0	0	0	0
	2 NITROPHENOL	0	0	0	0	0	0
	2,4 DIMETHYLPHENOL	0	0	0	0	0	0
	2,4 DICHLOROPHENOL	0	0	0	0	0	0
	P-CHLORO-M-CRESOL	0	0	0	0	0	0
	2,4,6 TRICHLOROPHENOL	0	0	0	0	0	0
	2,4 DINITROPHENOL	0	0	0	0	0	0
	4 NITROPHENOL	0	0	0	0	0	0
	4,6 DINITRO-O-CRESOL	0	0	1.1 *	0	0	0
	PENTACHLOROPHENOL	0	0	0	0	0	0
0.61							
	PHENOL	NS	0	0	0	0	0
	2 CHLOROPHENOL		0	0	0	0	0
	2 NITROPHENOL		0	0	0	0	0
	2,4 DIMETHYLPHENOL		0	0	0	0	0
	2,4 DICHLOROPHENOL		0	0	0	0	0
	P-CHLORO-M-CRESOL		0	0	0	0	0
	2,4,6 TRICHLOROPHENOL		0	0	0	0	0
	2,4 DINITROPHENOL		0	0	0	0	0
	4 NITROPHENOL		0	0	0	0	0
	4,6 DINITRO-O-CRESOL		0	0	0	3.9	0
	PENTACHLOROPHENOL		0	0	0	0	0

* DENOTES ESTIMATED RF

LYSIMETER # 8
WASTE WPW
SOIL LOAM

DEPTH (meters)	CHEMICAL	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25							
	PHENOL	0	0	0	NS	0	0
	2 CHLOROPHENOL	0	0	0		0	0
	2 NITROPHENOL	0	0	0		0	0
	2,4 DIMETHYLPHENOL	1.3 *	0	0		0	1417.7
	2,4 DICHLOROPHENOL	0	0	0		0	0
	P-CHLORO-M-CRESOL	0	0	0		0	0
	2,4,6 TRICHLOROPHENOL	0	0	3.7		0	0
	2,4 DINITROPHENOL	0	0	0		0	3682.5 *
	4 NITROPHENOL	0	0	0		0	0
	4,6 DINITRO-O-CRESOL	0	0	0		0	0
	PENTACHLOROPHENOL	0	0	0		78.1 *	0
0.41							
	PHENOL	0	0	0	0	0	0
	2 CHLOROPHENOL	0	0	0	0	0	0
	2 NITROPHENOL	0	0	0	0	0	0.8
	2,4 DIMETHYLPHENOL	0.1 *	0	0	0	0	0
	2,4 DICHLOROPHENOL	0	0	0	0	0	0
	P-CHLORO-M-CRESOL	0	0	0	0	0	0
	2,4,6 TRICHLOROPHENOL	0	0	0	0	0	0
	2,4 DINITROPHENOL	0	0	0	0	0	0
	4 NITROPHENOL	0	0	0	0	0	0
	4,6 DINITRO-O-CRESOL	0	0	7.7 *	0	0	0
	PENTACHLOROPHENOL	1.4 *	0	0	0	0	0
0.61							
	PHENOL	NS	0	0	NS	0	0
	2 CHLOROPHENOL		0	0		0	0
	2 NITROPHENOL		0	0		0	0
	2,4 DIMETHYLPHENOL		0	0		0	0
	2,4 DICHLOROPHENOL		0	0		0	0
	P-CHLORO-M-CRESOL		0	0		0	0
	2,4,6 TRICHLOROPHENOL		0	0		0	0
	2,4 DINITROPHENOL		0	0		0	0
	4 NITROPHENOL		0	0		0	0
	4,6 DINITRO-O-CRESOL		0	0		0	0
	PENTACHLOROPHENOL		0	0		3.1 *	0

* DENOTES ESTIMATED RF

LYSIMETER # 12
WASTE WPW
SOIL LOAM

DEPTH (meters)	CHEMICAL	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25							
	PHENOL	0	NS	0	NS	NA	0
	2 CHLOROPHENOL	0		0			0
	2 NITROPHENOL	0		0			0
	2,4 DIMETHYLPHENOL	0		0			0
	2,4 DICHLOROPHENOL	0		0			0
	P-CHLORO-M-CRESOL	0		0			0
	2,4,6 TRICHLOROPHENOL	0		0			0
	2,4 DINITROPHENOL	0		0			0
	4 NITROPHENOL	0		0			0
	4,6 DINITRO-O-CRESOL	0		0			0
	PENTACHLOROPHENOL	0		0			0
0.41							
	PHENOL	NA	0	0	0	0	0
	2 CHLOROPHENOL		0	0	0	0	0
	2 NITROPHENOL		0	0	0	0	2.5
	2,4 DIMETHYLPHENOL		0	0	0	0	0
	2,4 DICHLOROPHENOL		0	0	0	0	0
	P-CHLORO-M-CRESOL		0	0	0	0	0
	2,4,6 TRICHLOROPHENOL		0	0	0	0	1.1 *
	2,4 DINITROPHENOL		0	0	0	0	0
	4 NITROPHENOL		0	0	0	0	0
	4,6 DINITRO-O-CRESOL		0	0	0	0	0
	PENTACHLOROPHENOL		0	0	0	0	0
0.61							
	PHENOL	NA	NS	0	0	0	0
	2 CHLOROPHENOL			0	0	0	0
	2 NITROPHENOL			0	0	0	0
	2,4 DIMETHYLPHENOL			0	0	0	0
	2,4 DICHLOROPHENOL			0	0	0	0
	P-CHLORO-M-CRESOL			0	0	0	0
	2,4,6 TRICHLOROPHENOL			0	0	0	0
	2,4 DINITROPHENOL			0	0	0	0
	4 NITROPHENOL			0	0	0	0
	4,6 DINITRO-O-CRESOL			0	0	0	0
	PENTACHLOROPHENOL			0	0	0	0

* DENOTES ESTIMATED RF

LYSIMETER # 14
WASTE WPW
SOIL CLAY

DEPTH (meters) CHEMICAL	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25						
PHENOL	0	NS	0	0	0	0
2 CHLOROPHENOL	0		0	0	0	0
2 NITROPHENOL	10.3 *		0	0	0	0
2,4 DIMETHYLPHENOL	0		0	0	0	0
2,4 DICHLOROPHENOL	0		0	0	0	0
P-CHLORO-M-CRESOL	0		0	0	0	0
2,4,6 TRICHLOROPHENOL	0		0	0	0	0
2,4 DINITROPHENOL	0		0	0	0	0
4 NITROPHENOL	0		0	0	0	0
4,6 DINITRO-O-CRESOL	0		0	0	0	0
PENTACHLOROPHENOL	0		0	0	0	0
0.41						
PHENOL	NS	0	0	0	0	6.8
2 CHLOROPHENOL		0	0	0	0	0
2 NITROPHENOL		0	0	0	0	0
2,4 DIMETHYLPHENOL		0	0	0	0	26.6
2,4 DICHLOROPHENOL		0	0	0	0	0
P-CHLORO-M-CRESOL		0	0	0	0	2.7 *
2,4,6 TRICHLOROPHENOL		0	0	0	0	0
2,4 DINITROPHENOL		0	0	0	0	0
4 NITROPHENOL		0	0	0	0	0
4,6 DINITRO-O-CRESOL		0	0	0	0	0
PENTACHLOROPHENOL		0	0	0	0	0
0.61						
PHENOL	NA	NS	NA	NA	0	0
2 CHLOROPHENOL					0	0
2 NITROPHENOL					0	0
2,4 DIMETHYLPHENOL					0	0
2,4 DICHLOROPHENOL					0	0
P-CHLORO-M-CRESOL					0	0
2,4,6 TRICHLOROPHENOL					0	32.8
2,4 DINITROPHENOL					0	0
4 NITROPHENOL					0	0
4,6 DINITRO-O-CRESOL					0	305.0
PENTACHLOROPHENOL					0	113.0

* DENOTES ESTIMATED RF

LYSIMETER # 21
WASTE WPW
SOIL CLAY

DEPTH (meters)	CHEMICAL	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25							
	PHENOL	0	NS	0	NS	0	0
	2 CHLOROPHENOL	0		0		0	0
	2 NITROPHENOL	0		0		0	0
	2,4 DIMETHYLPHENOL	0		0		0	0
	2,4 DICHLOROPHENOL	0		0		0	0
	P-CHLORO-M-CRESOL	0		0		0	0
	2,4,6 TRICHLOROPHENOL	0		0		0	105.2
	2,4 DINITROPHENOL	5.1 *		0		0	0
	4 NITROPHENOL	0		0		0	0
	4,6 DINITRO-O-CRESOL	0		0		0	0
	PENTACHLOROPHENOL	0		0		0	0
0.41							
	PHENOL	0	NS	0	0	NA	0
	2 CHLOROPHENOL	0		0	0		0
	2 NITROPHENOL	0		0	0		0
	2,4 DIMETHYLPHENOL	1.7 *		0	0		0
	2,4 DICHLOROPHENOL	0		0	0		0
	P-CHLORO-M-CRESOL	0		0	0		0
	2,4,6 TRICHLOROPHENOL	0		0	0		0
	2,4 DINITROPHENOL	0		0	0		0
	4 NITROPHENOL	0		0	0		0
	4,6 DINITRO-O-CRESOL	0		0.9 *	0		0
	PENTACHLOROPHENOL	0		0	0		0
0.61							
	PHENOL	NA	NS	NA	NS	0	NS
	2 CHLOROPHENOL					0	
	2 NITROPHENOL					0	
	2,4 DIMETHYLPHENOL					0	
	2,4 DICHLOROPHENOL					0	
	P-CHLORO-M-CRESOL					0	
	2,4,6 TRICHLOROPHENOL					0	
	2,4 DINITROPHENOL					0	
	4 NITROPHENOL					0	
	4,6 DINITRO-O-CRESOL					0	
	PENTACHLOROPHENOL					0	

* DENOTES ESTIMATED RF

LYSIMETER # 24
WASTE WPW
SOIL CLAY

DEPTH (meters) CHEMICAL	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25						
PHENOL	NA	NS	0	0	0	0
2 CHLOROPHENOL			0	0	0	0
2 NITROPHENOL			0	0	0	0
2,4 DIMETHYLPHENOL			0	0	0	0
2,4 DICHLOROPHENOL			0	0	0	0
P-CHLORO-M-CRESOL			0	0	0	0
2,4,6 TRICHLOROPHENOL			0	0	0	0
2,4 DINITROPHENOL			0	0	0	0
4 NITROPHENOL			0	0	0	0
4,6 DINITRO-O-CRESOL			2.0 *	0	0	0
PENTACHLOROPHENOL			0	0	0	0
0.41						
PHENOL	NS	NS	C	0	0	0
2 CHLOROPHENOL			0	0	0	0
2 NITROPHENOL			0	0	0	0
2,4 DIMETHYLPHENOL			0	0	0	0
2,4 DICHLOROPHENOL			0	0	0	0
P-CHLORO-M-CRESOL			0	0	0	0
2,4,6 TRICHLOROPHENOL			0	0	0	0
2,4 DINITROPHENOL			0	0	0	0
4 NITROPHENOL			0	0	0	0
4,6 DINITRO-O-CRESOL			0.5 *	0	37.5 *	0
PENTACHLOROPHENOL			0	0	0	0
0.61						
PHENOL	NA	NS	NA	0	0	0
2 CHLOROPHENOL				0	0	0
2 NITROPHENOL				0	0	0
2,4 DIMETHYLPHENOL				0	0	0
2,4 DICHLOROPHENOL				0	0	0
P-CHLORO-M-CRESOL				0	0	0
2,4,6 TRICHLOROPHENOL				0	0	0
2,4 DINITROPHENOL				0	0	0
4 NITROPHENOL				0	0	0
4,6 DINITRO-O-CRESOL				0	48.0 *	58.6
PENTACHLOROPHENOL				0	0	0

* DENOTES ESTIMATED RF

LYSIMETER # 26
WASTE WPW
SOIL SAND

DEPTH (meters)	CHEMICAL	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25							
	PHENOL	0	NS	0	0	0	NS
	2 CHLOROPHENOL	0		0	0	0	
	2 NITROPHENOL	0		0	0	0	
	2,4 DIMETHYLPHENOL	0		0	0	0	
	2,4 DICHLOROPHENOL	0		0	0	0	
	P-CHLORO-M-CRESOL	0		0	0	0	
	2,4,6 TRICHLOROPHENOL	0		0	0	0	
	2,4 DINITROPHENOL	0.5 *		0	0	0	
	4 NITROPHENOL	0		0	0	0	
	4,6 DINITRO-O-CRESOL	0		0	0	15.3	
	PENTACHLOROPHENOL	0		0	0	0	
16"							
	PHENOL	0	0	0	0	0	0
	2 CHLOROPHENOL	0	0	0	0	0	0
	2 NITROPHENOL	0	0	0	0	0	0
	2,4 DIMETHYLPHENOL	3.7 *	0	0	0	0	0
	2,4 DICHLOROPHENOL	0	0	0	0	0	0
	P-CHLORO-M-CRESOL	0	0	0	0	0	0
	2,4,6 TRICHLOROPHENOL	0	0	0	0	0	2.7
	2,4 DINITROPHENOL	0	0	0	0	0	0
	4 NITROPHENOL	0	0	0	0	0	0
	4,6 DINITRO-O-CRESOL	0	0	0	0	0	0
	PENTACHLOROPHENOL	0	0	0	0	0	0
24"							
	PHENOL	NA	NS	0	0	0	0
	2 CHLOROPHENOL			0	0	0	0
	2 NITROPHENOL			0	0	0	0
	2,4 DIMETHYLPHENOL			0	0	0	0
	2,4 DICHLOROPHENOL			0	0	0	0
	P-CHLORO-M-CRESOL			0	0	0	0
	2,4,6 TRICHLOROPHENOL			0	0	0	22.3
	2,4 DINITROPHENOL			0	0	0	0
	4 NITROPHENOL			0	0	0	0
	4,6 DINITRO-O-CRESOL			0	0	13.6	0
	PENTACHLOROPHENOL			0	0	0	0

* DENOTES ESTIMATED RF

LYSIMETER # 29
WASTE WPW
SOIL SAND

DEPTH (meters) CHEMICAL	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25						
PHENOL	0	0	0	0	0	NA
2 CHLOROPHENOL	0	0	0	0	0	
2 NITROPHENOL	0	0	0	0	0	
2,4 DIMETHYLPHENOL	0	0	0	0	0	
2,4 DICHLOROPHENOL	0	0	0	0	0	
P-CHLORO-M-CRESOL	0	0	0	0	0	
2,4,6 TRICHLOROPHENOL	0	0	0	0	0	
2,4 DINITROPHENOL	0	0	0	0	0	
4 NITROPHENOL	0	0	0	0	0	
4,6 DINITRO-O-CRESOL	0	0	0	0	0	
PENTACHLOROPHENOL	0	0	0	0	0	
0.41						
PHENOL	0	0	NA	0	0	NA
2 CHLOROPHENOL	0	0		0	0	
2 NITROPHENOL	0	0		0	0	
2,4 DIMETHYLPHENOL	0	0		0	0	
2,4 DICHLOROPHENOL	0	0		0	0	
P-CHLORO-M-CRESOL	0	0		0	0	
2,4,6 TRICHLOROPHENOL	0	0		0	0	
2,4 DINITROPHENOL	0	0		0	0	
4 NITROPHENOL	0	0		0	0	
4,6 DINITRO-O-CRESOL	0	0		0	0	
PENTACHLOROPHENOL	0	0		0	0	
0.61						
PHENOL	NA +	NS	NA	0	0	NA
2 CHLOROPHENOL				0	0	
2 NITROPHENOL				0	0	
2,4 DIMETHYLPHENOL				0	0	
2,4 DICHLOROPHENOL				0	0	
P-CHLORO-M-CRESOL				0	0	
2,4,6 TRICHLOROPHENOL				0	0	
2,4 DINITROPHENOL				0	0	
4 NITROPHENOL				0	0	
4,6 DINITRO-O-CRESOL				0	0	
PENTACHLOROPHENOL				0	0	

* DENOTES ESTIMATED RF
+ SAMPLE DESTROYED

LYSIMETER # 34
WASTE WPW
SOIL SAND

DEPTH (meters)	CHEMICAL	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25							
	PHENOL	NA +	0	0	0	NA	0
	2 CHLOROPHENOL		0	0	0		0
	2 NITROPHENOL		0	0	0		0
	2,4 DIMETHYLPHENOL		0	0	0		0
	2,4 DICHLOROPHENOL		0	0	0		0
	P-CHLORO-M-CRESOL		0	0	0		0
	2,4,6 TRICHLOROPHENOL		0	0	0		0.9
	2,4 DINITROPHENOL		0	0	0		0
	4 NITROPHENOL		0	0	0		0
	4,6 DINITRO-O-CRESOL		0	0.6	0		0
	PENTACHLOROPHENOL		0	0	0		0
0.41							
	PHENOL	NA +	0	0	0	0	0
	2 CHLOROPHENOL		0	0	0	0	0
	2 NITROPHENOL		0	0	0	0	0
	2,4 DIMETHYLPHENOL		0	0	0	0	0
	2,4 DICHLOROPHENOL		0	0	0	0	0
	P-CHLORO-M-CRESOL		0	0	0	0	0
	2,4,6 TRICHLOROPHENOL		0	0	0	0	0
	2,4 DINITROPHENOL		0	12.2 *	0	0	0
	4 NITROPHENOL		0	0	0	0	0
	4,6 DINITRO-O-CRESOL		0	18.2 *	0	35.1 *	0
	PENTACHLOROPHENOL		0	0	0	27.9 *	0
0.61							
	PHENOL	NA +	NS	0	0	0	0
	2 CHLOROPHENOL			0	0	0	0
	2 NITROPHENOL			0	0	0	0
	2,4 DIMETHYLPHENOL			0	0	0	0
	2,4 DICHLOROPHENOL			0	0	0	2.1
	P-CHLORO-M-CRESOL			0	0	0	0
	2,4,6 TRICHLOROPHENOL			0	0	0	2.2
	2,4 DINITROPHENOL			6.7	0	0	0
	4 NITROPHENOL			0	0	0	0
	4,6 DINITRO-O-CRESOL			2.6	0	0	0
	PENTACHLOROPHENOL			0	0	0	0

* DENOTES ESTIMATED RF
+ SAMPLES DESTROYED

Appendix E

Statistical comparison of the phenols and cresols concentrations measured in soil core and soil-pore water samples in three soils treated with wood preservative waste

TABLE E1. WOOD PRESERVATIVE WASTE

	Phenol Mean ± SD (n)	2 chlorophenol Mean ± SD (n)	2 nitrophenol Mean ± SD (n)	2,4-dimethylphenol Mean ± SD (n)	2,4-dichlorophenol Mean ± SD (n)
Sand Core	ID†	ID	ID	ID	ID
Pore	ID	ID	ID	ID	ID
Regression	ID	ID	ID	ID	ID
Loam Core	ID	ID	ID	ID	ID
Pore	ID	ID	ID	ID	ID
Regression	ID	ID	ID	ID	ID
Clay Core	ID	ID	ID	ID	ID
Pore	ID	ID	ID	ID	ID
Regression	ID	ID	ID	ID	ID

† ID = insufficient paired data to do statistical analysis.

TABLE E1. WOOD PRESERVING WASTE

		P-chloro-m-cresol Mean ± SD (n)	2,4,6-trichloro-phenol Mean ± SD (n)	2,4-dinitro-phenol Mean ± SD (n)	2,4-nitro-phenol Mean ± SD (n)	4,6-dinitro-o-cresol Mean ± SD (n)	Pentachlorophenol Mean ± SD (n)
Sand	Core	ID †	0.0a* ± 0.0(3)	ID	ID	14.0a ± 14.0(5)	ID
	Pore	ID	9.0a ± 11.0(3)	ID	ID	0.0a ± 0.0(5)	ID
	Regression	ID	NA ††	ID	ID	NA	ID
Loam	Core	ID	ID	ID	ID	3.4a ± 3.2(4)	27.3a ± 43.9(3)
	Pore	ID	ID	ID	ID	0.0a ± 0.0(4)	0.0a ± 0.0(3)
	Regression	ID	ID	ID	ID	NA	NA
Clay	Core	ID	ID	ID	ID	14.8a ± 21.9(6)	ID
	Pore	ID	ID	ID	ID	60.6a ± 122.0(6)	ID
	Regression	ID	ID	ID	ID	$P_2 = -1.07C + 76$ $r^2 = 0.04$ df = 5	ID

ID = insufficient paired data to do statistical analysis.
NA = regression analysis cannot be applied to this data set.
* = means within a given soil and chemical combination followed by the same letter do not differ significantly at p = 0.05.

APPENDIX F

Concentration of eight chemicals in soil-pore water ($\mu g\ L^{-1}$) and soil core ($\mu g\ kg^{-1}$) samples from undisturbed monoliths amended with solvent recovery sludge

LYSIMETER #7
WASTE SRS
SOIL LOAM

DEPTH (meters)	CHEMICAL	JAN 8 CORE	JAN 8 PORE	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25									
	ETHYLBENZENE	0	NS	2825.6	NS	1310.0	NS	NA	NS
	XYLENE	0		0		504.0			
	2-BUTOXYETHANOL	2.8E8		5.7E5		48312.4			
	1,2,4-TRIMETHYLBENZENE	0		0		0			
	ACETOPHENONE	0		0		0			
	2 PHENYL 2-PROPANOL	432.4		1317.2		0			
	ISOPHORONE	1476.0		2376.9		13400			
	NAPHTHALENE	0		0		0			
0.41									
	ETHYLBENZENE	0	NS	0	0	3630.0	81.2	NA	16.9
	XYLENE	0		0	0	1565.6	56.2		0
	2-BUTOXYETHANOL	40750.0		27767.2	4855.0	25111.6	1905.0		0
	1,2,4-TRIMETHYLBENZENE	0		0	0	0	32.5		0
	ACETOPHENONE	0		0	0	0	578.8		135.0
	2 PHENYL 2-PROPANOL	0		540.0	0	1200.0	1971.2		1235.9
	ISOPHORONE	436.0		1890.0	1225.0	3145.2	1913.8		2959.0
	NAPHTHALENE	18.4		0	0	0	45.0		0
0.61									
	ETHYLBENZENE	3217.0	NS	6080.9	NS	3994.5	122.5	NA	46.1
	XYLENE	0		0		0	125.0		0
	2-BUTOXYETHANOL	20959.5		57706.6		57469.4	1884.9		201.1
	1,2,4-TRIMETHYLBENZENE	0		355.7		0	237.0		0
	ACETOPHENONE	0		2143.5		0	364.7		190.1
	2 PHENYL 2-PROPANOL	0		1342.9		1129.1	1371.4		450.0
	ISOPHORONE	0		12971.8		3150.5	826.7		10128.4
	NAPHTHALENE	0		0		0	0		85.9

LYSIMETER #9
WASTE SRS
SOIL LOAM

DEPTH (meters)	CHEMICAL	JAN 8 CORE	JAN 8 PORE	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25									
	ETHYLBENZENE	0	NS	195.2	NS	0	755.3	NA	0
	XYLENE	0		0		0	0		0
	2-BUTOXYETHANOL	1.8E5		6684.0		6404.0	2880.2		546.6
	1,2,4-TRIMETHYLBENZENE	0		795.6		0	210.0		0
	ACETOPHENONE	0		0		235.2	2075.0		240.5
	2 PHENYL 2-PROPANOL	280.0		476.4		1415.2	6025.0		1100.0
	ISOPHORONE	602.4		1645.6		8906.4	3262.5		1408.9
	NAPHTHALENE	0		0		0	0		130.0
0.41									
	ETHYLBENZENE	12788.4	0	0	NS	845.6	NS	NA	NA
	XYLENE	0	0	0		0			
	2-BUTOXYETHANOL	0	76895.2	93982.4		10918.8			
	1,2,4-TRIMETHYLBENZENE	0	0	0		0			
	ACETOPHENONE	0	10951.6	0		0			
	2 PHENYL 2-PROPANOL	0	0	666.8		7646.0			
	ISOPHORONE	325.6	0	6833.2		4897.2			
	NAPHTHALENE	39.2	0	0		0			
0.61									
	ETHYLBENZENE	705.2	4255.0	5424.5	169.5	0	169.2	NA	81.9
	XYLENE	0	4425.0	0	507.5	0	278.9		28.3
	2-BUTOXYETHANOL	3690.9	0	15540.5	1038.9	32475.8	5136.4		405.9
	1,2,4-TRIMETHYLBENZENE	0	0	0	123.3	0	96.8		0
	ACETOPHENONE	0	605.0	0	144.2	0	407.4		463.9
	2 PHENYL 2-PROPANOL	0	4012.0	0	219.6	1072.5	2217.9		277.2
	ISOPHORONE	0	1016.0	0	1220.5	3740.8	3297.0		1078.6
	NAPHTHALENE	0	0	0	77.4	0	87.5		105.1

LYSIMETER #10
WASTE SRS
SOIL LOAM

DEPTH (meters)	CHEMICAL	JAN 8 CORE	JAN 8 PORE	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25									
	ETHYLBENZENE	0	NS	0	NS	2516.4	0	NA	0
	XYLENE	0		0		2230.8	0		155.8
	2-BUTOXYETHANOL	88635.2		8095.2		67554.8	31097.8		0
	1,2,4-TRIMETHYLBENZENE	0		19.6		0	0		0
	ACETOPHENONE	0		0		0	1753.3		130.8
	2 PHENYL 2-PROPANOL	886.8		78.8		1508.4	282.2		513.5
	ISOPHORONE	2779.2		34.4		5228.8	85333.3		2446.2
	NAPHTHALENE	0		0		0	97.8		105.8
0.41									
	ETHYLBENZENE	NS	5310.0	NS	530.6	2582.8	0	NA	106.8
	XYLENE		6490.0		1181.1	0	0		0
	2-BUTOXYETHANOL		18283.3		2793.9	1.57E5	60618.0		430.1
	1,2,4-TRIMETHYLBENZENE		0		41.3	0	0		0
	ACETOPHENONE		0		144.3	0	756.0		0
	2 PHENYL 2-PROPANOL		0		368.5	1050.0	2680.0		884.9
	ISOPHORONE		0		1929.2	4265.6	35840.0		2865.8
	NAPHTHALENE		0		0	0	0		0
0.61									
	ETHYLBENZENE	1979.1	0	39.1	472.3	6146.4	141.3	NA	115.6
	XYLENE	0	0	0	577.2	0	124.9		0
	2-BUTOXYETHANOL	7850.9	1390.0	93.4	78.7	71858.6	19893.6		1161.8
	1,2,4-TRIMETHYLBENZENE	0	0	0	73.6	0	0		0
	ACETOPHENONE	303.10	0	0	83.5	0	228.4		260.6
	2 PHENYL 2-PROPANOL	0	0	0	178.6	1900.0	2014.1		1643.6
	ISOPHORONE	0	0	47.0	48.3	4091.5	23040.0		24827.2
	NAPHTHALENE	0	0	0	0	0	0		0

LYSIMETER #13
WASTE SRS
SOIL CLAY

DEPTH (meters)	CHEMICAL	JAN 8 CORE	JAN 8 PORE *	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25									
	ETHYLBENZENE	2319.6	0	0	NS	0	160.0	NA	42.9
	XYLENE	0	0	0		0	88.0		0
	2-BUTOXYETHANOL	1.8E5	4412.0	0		1.9E5	46182.0		225.7
	1,2,4-TRIMETHYLBENZENE	59.2	0	0		0	40.0		0
	ACETOPHENONE	0	0	0		0	128.0		137.1
	2 PHENYL 2-PROPANOL	520.0	0	0		1145.2	2042.0		2769.9
	ISOPHORONE	1235.2	206.0	0		8245.6	17648.0		32408.0
	NAPHTHALENE	0	0	0		0	5.88		0
0.41									
	ETHYLBENZENE	0	0	NA	NS	0	228.1	NA	NS
	XYLENE	0	0			0	0		
	2-BUTOXYETHANOL	3565.2	2576.0			81324.8	885.4		
	1,2,4-TRIMETHYLBENZENE	0	0			0	0		
	ACETOPHENONE	0	0			0	104.4		
	2 PHENYL 2-PROPANOL	0	88.0			0	360.7		
	ISOPHORONE	72.8	892.0			6400	645.5		
	NAPHTHALENE	0	0			0	0		
0.61									
	ETHYLBENZENE	3069.9	0	57.9	NS	2830.2	1316.5	NA	0
	XYLENE	0	0	30.8		2112.0	0		0
	2-BUTOXYETHANOL	9449.6	146960	4312.0		55721.9	65066.0		74130.4
	1,2,4-TRIMETHYLBENZENE	0	0	0		0	0		0
	ACETOPHENONE	0	0	0		0	177.6		0
	2 PHENYL 2-PROPANOL	0	0	0		0	1651.7		2304.3
	ISOPHORONE	2835.5	3430.0	33.4		7450.6	14117.0		8956.5
	NAPHTHALENE	0	0	20.5		0	0		0

* SOIL PORE-LIQUID SAMPLE CONCENTRATIONS OBTAINED FROM A COMPOSITE OF LYSIMETERS 13,15,19 AT THE SAME DEPTH.

LYSIMETER #15
WASTE SRS
SOIL CLAY

DEPTH (meters)	CHEMICAL	JAN 8 CORE	JAN 8 PORE *	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25									
	ETHYLBENZENE	0	0	0	NS	0	0	NA	NS
	XYLENE	0	0	814.4		0	0		
	2-BUTOXYETHANOL	4331.6	4412.0	32971.2		35194.4	5103.3		
	1,2,4-TRIMETHYLBENZENE	0	0	0		0	130.0		
	ACETOPHENONE	0	0	0		117.2	173.3		
	2 PHENYL 2-PROPANOL	0	0	0		328.8	2600.0		
	ISOPHORONE	80.0	206.0	1620.4		3415.6	2496.6		
	NAPHTHALENE	0	0	0		0	0		
0.41									
	ETHYLBENZENE	0	0	0	NS	NA	0	NA	0
	XYLENE	0	0	0			0		0
	2-BUTOXYETHANOL	0	2576.0	0			131.1		249.8
	1,2,4-TRIMETHYLBENZENE	0	0	0			0		0
	ACETOPHENONE	0	0	0			0		0
	2 PHENYL 2-PROPANOL	0	88.0	0			136.6		0
	ISOPHORONE	38.0	892.0	139.6			322.2		513.8
	NAPHTHALENE	0	0	0			0		0
0.61									
	ETHYLBENZENE	1877.7	0	0	NS	551.7	0	NA	NS
	XYLENE	0	0	0		0	0		
	2-BUTOXYETHANOL	1793.1	14696.0	1601.1		13202.2	0		
	1,2,4-TRIMETHYLBENZENE	0	0	0		0	0		
	ACETOPHENONE	0	0	0		775.2	0		
	2 PHENYL 2-PROPANOL	0	0	0		1032.2	0		
	ISOPHORONE	0	343.0	0		4399.5	726.0		
	NAPHTHALENE	0	0	0		0	0		

* SOIL PORE-LIQUID SAMPLE CONCENTRATIONS OBTAINED FROM A COMPOSITE OF LYSIMETERS 13,15,19 AT THE SAME DEPTH.

LYSIMETER #19
WASTE SRS
SOIL CLAY

DEPTH (meters)	CHEMICAL	JAN 8 CORE	JAN 8 PORE *	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25									
	ETHYLBENZENE	4331.6	0	0	NS	2270.4	242.5	NA	2720.0
	XYLENE	0	0	0		2439.6	0		0
	2-BUTOXYETHANOL	84000	4412.0	1.2E6		42800	59702		171030
	1,2,4-TRIMETHYLBENZENE	0	0	0		0	87.5		0
	ACETOPHENONE	0	0	940.8		0	137.5		970.0
	2 PHENYL 2-PROPANOL	273.2	0	1270.4		727.2	3680.0		50610.0
	ISOPHORONE	596.8	206.0	10507.6		6000.0	18255		291680
	NAPHTHALENE	0	0	0		0	0		0
0.41									
	ETHYLBENZENE	0	0	0	0	0	40.0	NA	45.0
	XYLENE	0	0	0	0	0	0		0
	2-BUTOXYETHANOL	0	2576.0	15986.8	0	31990.8	186.5		245.0
	1,2,4-TRIMETHYLBENZENE	0	0	0	0	0	0		0
	ACETOPHENONE	0	0	0	0	0	0		65.0
	2 PHENYL 2-PROPANOL	0	88.0	0	0	1176.8	290.8		3021.2
	ISOPHORONE	0	892.0	178.4	177.6	5384.8	157.6		11365.0
	NAPHTHALENE	0	0	0	0	0	0		265.0
0.61									
	ETHYLBENZENE	273.3	0	8163.5	NS	2466.5	8367.7	NA	40.0
	XYLENE	0	0	7670.9		0	0		0
	2-BUTOXYETHANOL	8052.2	14696	32207.2		7548.0	0		1000.0
	1,2,4-TRIMETHYLBENZENE	0	0	1068.4		0	0		0
	ACETOPHENONE	0	0	0		145.1	0		60.0
	2 PHENYL 2-PROPANOL	0	0	3783.3		1604.3	1871.9		670.0
	ISOPHORONE	1126.0	343	3784.6		347.6	745.0		3580.0
	NAPHTHALENE	0	0	0		0	0		0

* SOIL PORE-LIQUID SAMPLE CONCENTRATIONS OBTAINED FROM A COMPOSITE OF LYSIMETERS 13,15,19 AT THE SAME DEPTH.

LYSIMETER #30
WASTE SRS
SOIL SAND

DEPTH (meters)	CHEMICAL	JAN 8 CORE	JAN 8 PORE	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25	ETHYLBENZENE	0	73175	1019.6	NS	7108.4	0	NA	0
	XYLENE	0	5652.0	0		0	0		0
	2-BUTOXYETHANOL	1.5E5	31960	1.1E5		29630	8920.0		3649.0
	1,2,4-TRIMETHYLBENZENE	95.2	0	0		0	0		0
	ACETOPHENONE	0	7702.1	0		375.6	2495.0		138.2
	2 PHENYL 2-PROPANOL	1274.8	0	0		0	14375		1103.4
	ISOPHORONE	4280.8	19643.7	8406.8		2344.0	8730.0		613.5
	NAPHTHALENE	0	0	0		0	890.0		31.0
0.41	ETHYLBENZENE	NA	0	0	762.2	4082.8	NS	NA	0
	XYLENE		0	0	1.3E6	0			0
	2-BUTOXYETHANOL		0	55772	8302.4	1.3E5			0
	1,2,4-TRIMETHYLBENZENE		0	0	107.5	0			0
	ACETOPHENONE		0	0	188.6	0			49.4
	2 PHENYL 2-PROPANOL		0	0	1015.8	0			294.0
	ISOPHORONE		0	1020.0	1704.6	14940			1470.6
	NAPHTHALENE		0	0	32.7	0			0
0.61	ETHYLBENZENE	2207.6	NS	1965.1	3238.7	2697.7	441.7	NA	0
	XYLENE	0		0	4360.8	0	0		0
	2-BUTOXYETHANOL	0		11494	0	23807	0		0
	1,2,4-TRIMETHYLBENZENE	0		0	203.9	0	0		0
	ACETOPHENONE	0		0	618.1	226.5	537.4		213.2
	2 PHENYL 2-PROPANOL	0		0	261.9	774.0	673.5		580.0
	ISOPHORONE	0		428.1	0	1578.1	1426.6		1778.6
	NAPHTHALENE	0		0	0	0	214.6		0

LYSIMETER #31
WASTE SRS
SOIL SAND

DEPTH (meters)	CHEMICAL	JAN 8 CORE	JAN 8 PORE	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25	ETHYLBENZENE	0	2886.1	12728	NS	2566.4	89.6	NA	0
	XYLENE	0	0	0		2251.6	109.8		0
	2-BUTOXYETHANOL	1.7E5	227162	47722		1.2E5	874.4		387.2
	1,2,4-TRIMETHYLBENZENE	0	0	0		0	51.9		0
	ACETOPHENONE	68.0	11702	0		164.0	137.0		91.7
	2 PHENYL 2-PROPANOL	1317.2	1.7E5	0		194.4	602.1		0
	ISOPHORONE	5177.6	27029	3190.0		9226.8	9226.8		407.2
	NAPHTHALENE	0	0	0		0	31.3		0
0.41	ETHYLBENZENE	0	0	0	326.9	2235.6	NS	NA	0
	XYLENE	0	0	0	728.1	0			0
	2-BUTOXYETHANOL	3.5E5	5954.4	22268	0	2.5E5			852.1
	1,2,4-TRIMETHYLBENZENE	0	0	0	0	0			268.0
	ACETOPHENONE	0	0	0	174.8	0			104.9
	2 PHENYL 2-PROPANOL	691.6	0	644.4	0	0			889.4
	ISOPHORONE	3044.0	8828.0	5477.6	160.7	15118			639.3
	NAPHTHALENE	0	0	0	0	0			96.4
0.61	ETHYLBENZENE	3551.2	NS	2007.2	NS	2429.1	732.8	NA	NS
	XYLENE	0		0		0	0		
	2-BUTOXYETHANOL	20785		16352		39820	255.5		
	1,2,4-TRIMETHYLBENZENE	0		0		0	0		
	ACETOPHENONE	0		93.6		0	110.3		
	2 PHENYL 2-PROPANOL	0		10971		2734.4	0		
	ISOPHORONE	275.3		1700.7		3150.4	2629.3		
	NAPHTHALENE	0		0		0	364.1		

LYSIMETER #32
WASTE SRS
SOIL SAND

DEPTH (meters)	CHEMICAL	JAN 8 CORE	JAN 8 PORE	FEB 7 CORE	FEB 7 PORE	APRIL 20 CORE	APRIL 20 PORE	JULY 20 CORE	JULY 20 PORE
0.25	ETHYLBENZENE	5820.8	1836.5	923.2	NS	0	NS	NA	0
	XYLENE	0	6817.6	0		0			0
	2-BUTOXYETHANOL	11709	9438.8	52800		17331			1765.0
	1,2,4-TRIMETHYLBENZENE	0	228.2	0		0			0
	ACETOPHENONE	50.8	4316.5	0		0			530.0
	2 PHENYL 2-PROPANOL	0	4001.2	908.0		1272.8			2180.0
	ISOPHORONE	995.6	14148	3144.8		2419.2			3862.5
	NAPHTHALENE	0	147.1	0		0			87.5
0.41	ETHYLBENZENE	0	NS	0	NS	0	172.9	NA	0
	XYLENE	0		0		0	0		0
	2-BUTOXYETHANOL	0		53600		77143	0		6043.1
	1,2,4-TRIMETHYLBENZENE	90.8		0		0	0		271.3
	ACETOPHENONE	20.8		0		0	297.6		491.2
	2 PHENYL 2-PROPANOL	0		0		14800	3500		679.7
	ISOPHORONE	284.4		8137.2		77330	608.0		2955.5
	NAPHTHALENE	33.2		0		0	224.1		0
0.61	ETHYLBENZENE	1445.2	0	1591.3	38.0	1291.1	474.5	NA	0
	XYLENE	0	0	0	106.0	0	95.7		0
	2-BUTOXYETHANOL	0	795.0	5454.2	2863.0	34480.1	0		856.0
	1,2,4-TRIMETHYLBENZENE	0	87.0	171.5	56.0	0	95.0		0
	ACETOPHENONE	0	0	0	80.0	0	148.1		0
	2 PHENYL 2-PROPANOL	0	0	5271.1	125.0	1675.6	1013.3		0
	ISOPHORONE	0	652.0	1245.8	757.0	2352.4	1748.2		312.7
	NAPHTHALENE	0	0	0	88.0	0	0		0

APPENDIX G

Statistical comparison of the aromatic concentrations measured in soil core and soil-pore water samples in three soils treated with solvent recovery sludge

TABLE G1. SOLVENT RECOVERY SLUDGE

		2 phenyl-2-propanol Mean ± SD (n)	Acetophenone Mean ± SD (n)	Trimethylbenzene Mean ± SD (n)	Naphthalene Mean ± SD (n)
Sand	Core	2098a*± 3926(14)	68a ± 118(13)	33.4a ± 65.1(8)	0.0a ± 0.0(8)
	Pore	13969a ± 45069(14)	2193a ± 3646(13)	103.8a ± 77.1(8)	249.0b ± 282.0(8)
	Regression	P_2= -0.066C + 15348	P_2= 0.92C + 2130	P_2= -0.6C + 124	NA††
		r^2 = 0.003 df = 1	r^2 =0.0009 df = 12	r^2 = 0.26 df = 7	
Loam	Core	892a ± 662(11)	45a ± 106(12)	0.0a ± 0.0(6)	7.8a ± 17.4(5)
	Pore	1907a ± 1857(11)	1496a ± 3047(12)	129.0b ± 79.0(6)	61.6a ± 39.8(5)
	Regression	P_2= 0.723C + 1261.8	P_2= -2.6C + 1611	NA	P_2= -1.97C + 77
		r^2 = 0.07 df = 11	r^2 =0.008 df = 11		r^2 = 0.75 df = 4
Clay	Core	524a ± 559(13)	148a ± 283(7)	14.8a ± 29.5(4)	ID†
	Pore	982a ± 1239(13)	103a ± 75(7)	64.5a ± 56.6(4)	ID
	Regression	P_2= 0.675C + 628.3	P_2= -0.18C + 130	P_2= -1.5C + 86	ID
		r^2 = 0.09 df = 1	r^2 = 0.46 df = 6	r^2 = 0.58 df = 3	

† ID = insufficient paired data to do statistical analysis.

†† NA = regression analysis cannot be applied to this data set.

* = means within a given soil and chemical combination followed by the same letter do not differ significantly at p = 0.05.

TABLE G1. SOLVENT RECOVERY SLUDGE

		Isophorone Mean ± SD (n)	Ethylbenzene Mean ± SD (n)	Xylene Mean ± SD (n)	2-Butoxyethanol Mean ± SD (n)
Sand	Core	54510a* ± 199976(15)	1922a ± 2194(14)	282a ± 796(8)	73438b ± 93150(15)
	Pore	6486a ± 8199(15)	6013a ± 19359(14)	164734a ± 458725(8)	19768a ± 57968(15)
	Regression	P_2= -0.0079C + 6918	P_2= -2.25C + 10340	P_2= -83.54C+188251.6	P_2= 0.20C + 4844
		r^2 = 0.037 df = 14	r^2 = 0.07 df = 13	r^2 = 0.02 df = 1	r^2 = 0.11 df = 14
Loam	Core	2899a ± 2666(12)	3390a ± 3802(11)	475a ± 897(8)	36371a ± 44061(13)
	Pore	13085a ± 25356(12)	561a ± 1247(11)	762a ± 1495(8)	15974a ± 25332(13)
	Regression	P_2= 3.71C + 2319	P_2= 0.11C + 920	P_2= -0.498C + 998.46	P_2= 0.26C + 6612
		r^2 = 0.15 df = 11	r^2 = 0.10 df = 10	r^2 = 0.09 df = 1	r^2 = 0.20 df = 12
Clay	Core	2746a ± 2983(17)	1793a ± 1460(11)	1517a ± 1324(3)	47524a ± 59307(17)
	Pore	3649a ± 6323(17)	941a ± 2493(11)	29a ± 51(3)	21161a ± 38920(17)
	Regression	P_2= 1.52C - 537.3	P_2= 0.3C + 406	P_2= -0.038C + 87.10	P_2= 0.03C + 19734
		r^2 = 0.52 df = 16	r^2 = 0.03 df = 10	r^2 = 0.98 df = 1	r^2 = 0.002 df = 16

* = means within a given soil and chemical combination followed by the same letter do not differ significantly at p = 0.05.

APPENDIX H

Octanol:water partition coefficients (Log K_{ow}) for most chemicals mentioned in this report

TABLE H1. OCTANOL:WATER PARTITION COEFFICIENTS (LOG K_{OW}) FOR MOST CHEMICALS MENTIONED IN THIS REPORT

Chemical Class	Chemical	Log K_{ow}	Chemical Class	Chemical	Log K_{ow}	Chemical Class	Chemical	Log K_{ow}
Alkanes[a]	Octane	4	Aromatics[b]	Acetophenone[d]	1.58	PNA's[b,c]	Acenaphthene	3.92
	Nonane	4.51		Ethylbenzene	3.13		Acenaphthylene	4.07
	Decane	5.01		Isophorone	1.70		Anthracene	4.54
	Undecane	5.58		Naphthalene	3.35		Chrysene	5.79
	Dodecane	6.1		o-xylene	3.13		Fluoranthene	5.33
	Tridecane	6.65		m-xylene	3.20		Fluorene	4.18
	Tetradecane	7.2		p-xylene	3.18		Phenanthrene	4.46
	Pentadecane	7.72					Pyrene	5.18
	Hexadecane	8.25	Phenols[c]	Phenol	1.46			
	Heptadecane	8.79		p-chloro-m-cresol	2.95	Pesticides[c,d]	Aldicarb[e]	0.7
	Octadecane	9.32		2-chlorophenol	2.17		ppDDD	6.02
	Nonadecane	9.86		2,4 dichlorophenol	2.75		ppDDE	5.69
	Eicosane	10.39		2,4 dimethylphenol	2.5		ppDDT	6.19
	Heneicosane	10.93		2,4 dinitrophenol	1.53			
	Docosane	11.46		4,6 dinitro-o-cresol	2.85			
	Tricosane	12.00		2-nitrophenol	1.76			
	Tetracosane	12.53		4-nitrophenol	1.91			
	Pentacosane	13.07		2,4,6-trichlorophenol	3.38			
				Pentachlorophenol	5.01			

a. From Coates et al. (1985) Environ. Sci. Technol. 19:628-632.
b. From Miller and Wasik (1985) Environ. Sci. Technol 19:522-529
c. From Callahan et al. (1979) EPA-440/4-79-029 a&b.
d. From Veith et al. (1979) Water Research 13:43-47.
e. Knisel, W. G. (ed.). CREAMS, USDA, Conservation Research Report No. 26, 640 pp.

APPENDIX I

GLOSSARY OF TERMS

GLOSSARY

Adsorption (sorption) - The process by which atoms, molecules, or ions are taken up and retained on the surfaces of solids by chemical or physical binding, e.g., the adsorption of cations by negatively charged minerals.

Aggregate - A unit of soil structure formed by natural processes as opposed to artificial processes, and generally <10 mm in diameter.

Aggregation - The process whereby primary soil particles (sand, silt, clay) are bounded together by natural forces and substances derived from root exudates and microbial activity.

Bentonite - Clays, largely composed of smectite clay minerals, produced by the alteration of volcanic ash in situ.

Bubbling Pressure - The pressure (or vacuum) required to force air through a porous ceramic cup after it has been thoroughly wetted with water. The smaller the pore size in the cup, the higher this pressure will be.

Bulk Density, Soil - The mass of dry soil per unit bulk volume. The bulk volume is determined before drying to constant weight at 105°C.

Calcareous Soil - Soil containing sufficient free $CaCO_3$, and/or $MgCO_3$ to effervesce visibly when treated with cold 0.1M HCl. These soils usually contain >100 to 200 g kg^{-1} $CaCO_3$ equivalent.

Cation Exchange Capacity (CEC) - The sum of exchangeable cations that a soil, soil constituent, or other material can adsorb at a specific pH.

Coarse Texture - The texture exhibited by sands, loamy sands, and sandy loams except very fine sandy loam.

Field Capacity, in situ (field moisture capacity) - The amount of water remaining in a soil 2 or 3 days after having been wetted and after free drainage is negligible.

Fine Texture - Consisting of or containing large quantities of the fine fractions, particularly of silt and clay. (Includes all clay loams and clays; that is, clay loam, sandy clay loam, silty clay loam, sandy clay, silty clay, and clay textural classes. Sometimes subdivided into clayey texture and moderately fine texture).

Friable - A consistency term pertaining to the ease of crumbling of soils.

Ion Selective Electrode - An electrochemical sensor, the potential of which (in conjunction with a suitable reference electrode) depends on the logarithm of the activity of a given ion in aqueous solution.

Land Treatment - The controlled application of hazardous wastes onto or into the aerobic surface soil horizon, accompanied by continued monitoring and management, to alter the physical, chemical, and biological state of the waste to render it less hazardous. The practice simultaneously constitutes treatment and final disposal.

Leaching - The removal of materials in solution from the soil.

Lysimeter - A device for measuring percolation and leaching losses from a column of soil under controlled conditions.

Macropore - A soil pore with a radius >75 μm.

Partition Coefficient, n-octanol:water, (K_{ow}) - The ratio of the equilibrium concentrations (c) of a dissolved substance in a two-phase (n-octanol:water) system consisting of two largely immiscible solvents. In the case n-octanol and water,

$$K_{ow} = \frac{C_{octanol}}{C_{water}}$$

the n-octanol:water partition coefficient (K_{ow}) therefore is the quotient of two concentrations and is usually given in the form of its logarithm to base ten ($\log K_{ow}$).

Ped - A unit of soil structure such as an aggregate, crumb, prism, block, or granule, formed by natural processes (in contrast with a clod, which is formed artificially).

Pore-Size Distribution - The volume of the various sizes of pores in a soil. Expressed as percentages of the bulk volume (soil plus pore space).

Pore Volume - Total space not occupied by soil particles in a bulk volume of soil.

Silt Loam - A soil textural class containing a large amount of silt and small quantities of sand and clay.

Soil Structure - The combination or arrangement of primary soil particles into secondary particles, units, or peds. These secondary units may be, but usually are not, arranged in the profile in such a manner as to give a distinctive characteristic pattern. The secondary units are characterized and classified on the basis of size, shape, and degree of distinctness into classes, types, and grades, respectively. (See also aggregation).

Soil Survey - The systematic examination, description, classification, and mapping of soils in an area. Soil surveys are classified according to the kind and intensity of field examination.

Spatial Variability - The variation in soil properties both vertically downward through the soil profile and laterally across the soil surface at a given depth or with a given horizon.

Treatment Zone - The depth of soil relied upon to attenuate or degrade the undesirable constituents of the waste. Usually taken as not more than 1.5 M.

Unsaturated Zone - The geological profile extending from ground surface (including the treatment zone) to the upper surface of the principal water-bearing formation.